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# COAST GUARD CUTTER DUTY CYCLE AND PROPELLER/DIESEL ENGINE EFFICIENCY STUDY



REPRINT
MAY 1981



U.S. DEPARTMENT OF TRANSPORTATION

RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER • CAMBRIDGE MA 02142

PREPARED FOR UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT • WASHINGTON DC 20593

18 -D,TSC

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 19 CG-D-26-80 USCG-80-8 | AD-A101 567 | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| 6 COAST GUARD CUTTER DUTY CYCLE AND PROPELLER/ DIESEL ENGINE EFFICIENCY STUDY. | 11 May 1981 Reprint |
| | 6. Performing Organization Code |
| 7. Author(s) 10 Q.A. Baker, J. O. Storment | 8. Performing Organization Report No. DOT-TSC-USCG-80-8 11-4132-003/004 |
| 9. Performing Organization Name and Address: Southwest Research Institute* 622 Culebra Road San Antonio TX 78284 | 10. Work Unit No. (TRAIS) CG007/R1014 |
| 12 | 11. Contract or Grant No. 15 DOT-TSC-920 |
| 12. Sponsoring Agency Name and Address: U.S. Department of Transportation U.S. Coast Guard Office of Research and Development Washington DC 20593 | 13. Type of Report and Period Covered: 9 Final Report. Sep. 1975 — Aug. 1980 |
| | 14. Sponsoring Agency Code G-DMT-3 |

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center (DTS-332)
Cambridge MA 02142

16. Abstract


This report covers an investigation into methods to reduce the fuel consumption of the large main propulsion diesel engines used on 378 high-endurance and 210B medium-endurance Coast Guard cutters. This investigation involved, first, defining the duty cycles for the cutters and, second, analyzing the efficiency of the controllable pitch propellers and main diesel engines. Based on this information, cycle composite cutter fuel consumption figures were calculated and changes in the operational procedures of these cutters were recommended where fuel savings appeared to be possible. Methods of reducing fuel consumption which were analyzed were changes in the propeller pitch/engine speed combination needed to produce a given cutter speed, and possible single-engine operation at low cutter speeds.

A study of the duty cycle of an icebreaker is also included in the program.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| High Endurance Coast Guard Cutters, Medium-Endurance Coast Guard Cutters, Coast Guard Icebreakers, Fuel Consumption, Controllable Pitch Propellers, Duty Cycles, Diesel Engines | DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 88 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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## PREFACE

This work was performed for the U.S. Coast Guard Office of Research and Development through the Transportation Systems Center of the U.S. Department of Transportation. The Technical Monitor for the Coast Guard was Fred Weidner, and Robert Walter represented TSC.

The cooperation of the Commanding Officers and crews of the Coast Guard Cutters CHASE, GALLATIN, HAMILTON, VALIANT, DURABLE, DECISIVE, and WESTWIND in this program is acknowledged.

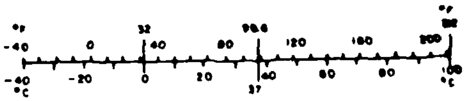
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |


## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# 1. INTRODUCTION

## 1.1 BACKGROUND

An investigation of methods to reduce fuel consumption and improve emissions of large in-service diesel engines used in locomotives and several classes of Coast Guard cutters was begun by Southwest Research Institute in November 1974, under Contract DOT-TSC-920. This report encompasses the portion of that program which dealt with the optimization of fuel consumption for several classes of the larger Coast Guard cutters. These classes include the 378-ft. High-Endurance cutters (378 WHEC), the 210-ft. B series Medium-Endurance cutters (210B WMEC), and Icebreakers (WAGB).

The fuel consumption of the main diesel engines of these cutters is of prime importance to the Coast Guard since they use a major portion of the diesel fuel consumed by the entire Coast Guard cutter fleet. A DOT report[1] placed this fuel consumption at $2.9 \times 10^7$ gallons, of which approximately 37%, or $1.8 \times 10^7$ gallons, was consumed by the diesel engines of the cutter classes of interest. However, this figure represents the fuel consumed by the main and auxiliary diesel power plants carried on board some of these cutters. The exact portion of usage by the main diesels alone is unknown, but a reasonable estimate would be that at least two-thirds of the fuel consumed could be attributed to the main diesel engines. There are slightly over 100 such engines in Coast Guard ships.[2]

Programmed variations in the operational characteristics of the medium- and high-endurance cutters (WMEC's and WHEC's) are possible since they are equipped with variable-pitch propellers directly driven by the main diesel engines through a fixed-ratio speed reduction system. [Icebreakers (WAGB) have fixed-pitch propellers.] This variable pitch feature allows for an infinite number of pitch/engine speed settings which will produce a given ship speed. However, the ships operate only at selected settings which are defined by a programmed pitch schedule. Optimization of the pitch schedule could produce acceptable cutter performance with minimum fuel consumption.

## 1.2 OBJECTIVES

The objectives of the tasks in this program were:

a. Define duty cycles for the high-endurance (378 WHEC) and medium-endurance (210B WMEC) cutters, and icebreakers (WAGB). That is, define the characteristic distribution of operating time among the various engine speed/pitch modes for each class of ship.

b. Obtain a set of time-based modal weighting factors which define the characteristic utilization for normal operation of the main diesel engines in these cutters.

c. Determine the overall effect of engine mode and propeller pitch changes on fuel consumption and cutter performance through analysis of propeller pitch/efficiency data for medium-endurance and high-endurance cutters.

## 1.3 APPROACH

Data needed to define the duty cycles for the three classes of Coast Guard cutters covered in this report were obtained by instrumenting one or more cutters of each class and, where possible, through analysis of ships' log books. Further information on cutter operating practices and systems was furnished by ships' personnel and by the Naval Engineering Maintenance Branch of the Coast Guard.

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[1] Willis, Lt., B., "WHEC 378 Fuel Consumption Study", U.S. Coast Guard Report Prepared by G-OP Energy Branch, March 11, 1980.

[2] Janes Fighting Ships, 1972-1973.

Analysis of propeller pitch/efficiency for the medium-endurance and high-endurance cutters required the use of design data for the controllable pitch propellers and for the cutters themselves. This information was obtained through the Coast Guard and from the technical literature. The performance maps for the main diesel engines were developed in Phase I of this program from information furnished by engine manufacturers, as well as from a search of published technical literature.[3]

The result of the study was an estimate of cutter fuel consumption through a correlation between propeller and engine performance at the various operating modes. These estimates were then weighted according to the duty cycle information (modal weighting factors) to produce cycle composite fuel consumption figures. With knowledge of propeller and engine performance, recommendations were made on operational changes which could reduce fuel consumption.

It should be pointed out that the Icebreakers were not included in the propeller pitch/efficiency study since they employed fixed pitch propellers and, as such, did not have the latitude for variable propeller performance as with the WHEC and WMEC. Consequently, the sole objective in working with the Icebreakers was to define their duty cycle.

[3]Storment, J. O., R. J. Mathis, and C. D. Wood, A Study of Fuel Economy and Emission Reduction Methods for Marine and Locomotive Diesel Engines, Report No. DOT-TSC-OST-75-41 or CG-D-124-75, Department of Transportation/U.S. Coast Guard, September 1975.

# 2. CONCLUSIONS

## 2.1 DUTY CYCLE DATA

a. Each ship, in both WHEC and WMEC classes, characteristically operated in a specific set of throttle positions which correspond to conditions of engine speed and load (or propeller pitch), and the percentage time spent in each throttle position was fairly constant from month to month.

b. The percentage time spent in each operating mode and the total accumulated time for the two main propulsion engines were very nearly equal for the WHEC's.

c. The distribution of percentage operating time among the throttle positions for the two engines on the WMEC's varied due to either frequent single-engine operation or the desire to balance power output between the two engines.

d. Because of frequent two-engine operation (one per propeller) and the desire to balance shaft speed for the pair of fixed-pitch propellers, the distribution of percentage operating time varied among the modes for the engines on the icebreaker WESTWIND, the only WAGB included in this study.

## 2.2 FUEL CONSUMPTION ANALYSIS FOR MEDIUM- AND HIGH-ENDURANCE CUTTERS

a. Fuel consumption decreased for both classes of ships as propeller pitch ratio was increased for a constant ship speed throughout the operating range when operating normally with both propellers driven.

b. The most substantial projected fuel savings resulted from a decrease in propeller pitch at constant engine speed, decreasing shaft horsepower and cutter speed for both WMEC and WHEC.

c. No significant reduction in fuel consumption appeared possible for the WMEC when operating normally by increasing pitch ratio at constant ship speed since the cutter is currently operating at or near a condition of minimum fuel usage.

d. Of the two propellers utilized on the WHEC's, the Escher-Wyss was found to be significantly more efficient, resulting in a decrease in fuel consumption of approximately 14% on a cycle composite basis over the Propulsion Systems, Inc. (PSI) design when operating on the current pitch schedule.

e. Fuel consumption savings are theoretically possible in the 2/3 and Full operating modes on the WHEC without sacrificing cutter speed if the pitch can be increased beyond the present limit of 1.0 to 1.4. The limitation here is the engine torque available to turn the prop at higher pitch settings.

f. Single-engine operation of the WHEC did not reduce fuel consumption at ship speeds of 10 knots or more. Single-engine operation is believed to be most beneficial below this speed; however, propeller and cutter performance data were not available to allow a firm conclusion on this point.

g. When operating with a single propeller, the free propeller should be rotating at the maximum pitch setting. A locked propeller results in a large increase in drag and, therefore, higher fuel consumption.

# 3. RECOMMENDATIONS

a. Obtain engine and cutter performance data for the WMEC's and WHEC's through cutter testing. The data should be extensive enough to reconstruct the propeller diagrams. Provisions should be made to measure engine fuel consumption, power output (possibly using a torsion meter), engine speed, propeller pitch, and ship speed for points throughout the operating range. As part of these tests, determine the maximum pitch which can be obtained throughout the diesel engine speed range and the resulting cutter speeds.

b. Compare the performance data to the present propeller diagrams to verify their accuracy. If necessary, correct the propeller diagrams to reflect true cutter operating characteristics. Ascertain that postulated mode changes are possible in practice and that they conserve fuel.

c. Expand the slow ship speed (less than 10 knots) portion of the WHEC propeller diagrams for single-engine and normal two-engine operation, calculate fuel rates for slow-speed operation, and determine if and when single-engine operation has merit. Verify the single-engine operation propeller diagrams through WHEC testing.

d. Perform an analysis of single-engine operation for medium-endurance cutters. Again, this type of operation is most advantageous in the ship speed range below 10 knots, and the analysis should concentrate on this region. This would require generation of a single-engine operation propeller diagram for this cutter class.

e. The Coast Guard should perform an in-house cost/benefit analysis to determine the advantages of replacing the WHEC Propulsion Systems, Inc. (PSI) propellers with the more efficient Escher-Wyss design. Because of the accuracy of the data on hand, performance data as obtained in recommendation 1 for both propeller designs should be the basis for the analysis.

# 4. DUTY CYCLE DATA ACQUISITION

## 4.1 PROPULSION SYSTEMS AND OPERATING MODES

### 4.1.1 High- and Medium-Endurance Cutters (WHEC's and WMEC's)

The propulsion systems on the high- and medium-endurance cutters employ a direct-drive concept in which the main propulsion units are coupled directly to variable pitch propellers through a constant-ratio gear reduction system. The main machinery on the WHEC's is a combined diesel engine/gas turbine (CODOG) arrangement in which operation is possible on either gas turbines or diesel engines. The first five WMEC's (210A class) were built with a combined diesel engine/gas turbine (CODAG) arrangement where gas turbines and/or diesel engines could be used. The remainder of the WMEC fleet (210B class) employed only diesel engines for propulsion, again utilizing the direct drive system.[4,5,6]

The diesel engines in both cutter classes operate only in a distinct set of modes which are defined by engine speed and propeller pitch. Mode selection from the pre-programmed pitch schedule is accomplished by the position of a control handle, one for each engine. The arrangement is such that, as the handle is moved from the lowest to the highest setting, propeller pitch is increased from zero to maximum at a constant engine idle speed, at which point speed is increased until it reaches its maximum value while pitch is held at the maximum value. Typical throttle schedules for these engines are plotted in Figures 4-1 and 4-2.

The schedule for the WHEC cutters also includes operating modes (Idle, 1/3, 2/3, Standard, Full, and Flank) which are the designated operating conditions of these ships and are associated with specific handle positions; typical values are shown in the table below. Normally, each ship defines its own schedule. Handle positions above 8 are nonfunctional for diesel engine operation; setting the handles in these positions results in handle position 8 operation. It should be noted that the WHEC is equipped with a continuous throttle control and, therefore, can be operated at conditions that lie between those shown in the table, although this is not done in normal practice.

TABLE 4-1. TYPICAL HIGH-ENDURANCE CUTTER OPERATING MODES

| MODE | HANDLE POSITION | PROPELLER PITCH RATIO | ENGINE RPM |
|---|---|---|---|
| Idle | 0 | 0 | 450 |
| 1/3 | 3 | 0.55 | 450 |
| 2/3 | 5.5 | 1.0 | 450 |
| Standard | 7 | 1.0 | 750 |
| Full | 8 | 1.0 | 900 |
| Flank | 8-10 | 1.0 | 900 |

[4]Wennberg, P. K., "The Design of the Main Propulsion Machinery Plant Installed in the USCG HAMILTON (WPG-715)", Society of Naval Architects and Marine Engineers Transactions, Vol. 74, 1966.

[5]Russel, H. E., "First Coast Guard High-Endurance Cutter in Twenty Years", Naval Engineers Journal, October 1965.

[6]Anonymous, "'Reliance' Class Cutters", Shipbuilding and Shipping Record, November 4, 1965.

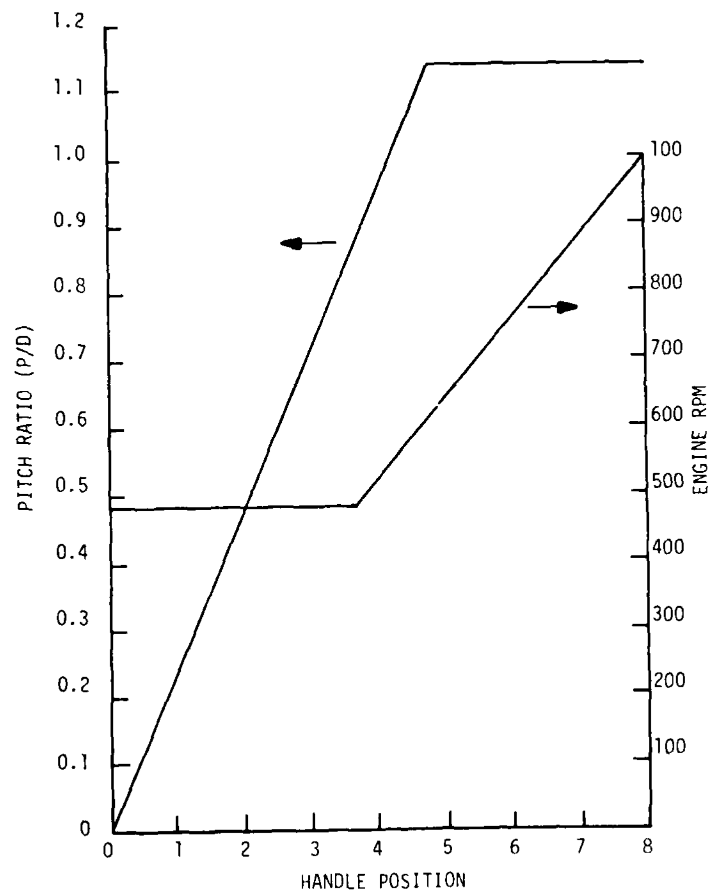


FIGURE 4-1. 210B WMEC THROTTLE SCHEDULE

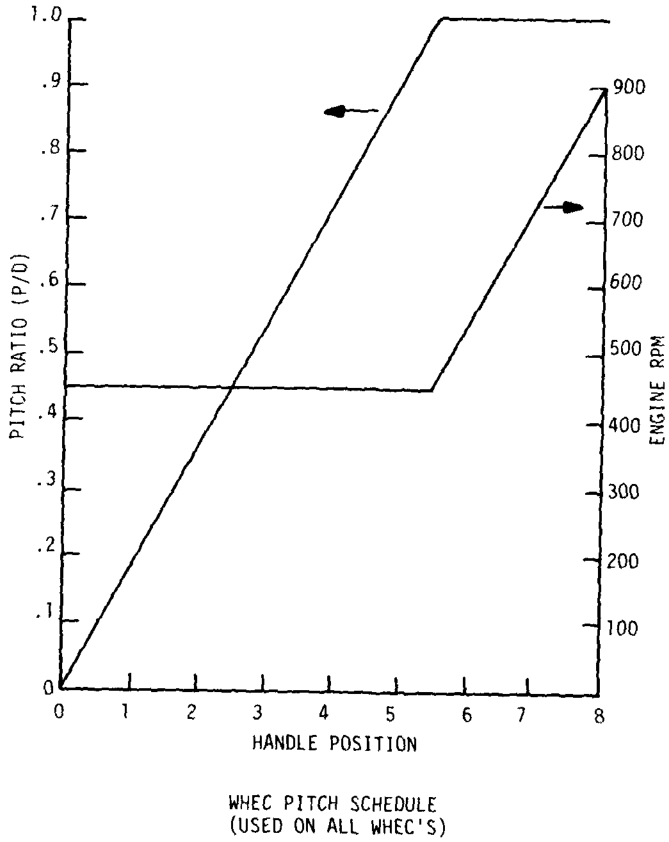


FIGURE 4-2. 378-FOOT WHEC THROTTLE SCHEDULE

The main diesel engines of the WMEC and WHEC are equipped with governors that maintain the designated engine speed (or shaft speed) for a particular throttle position as long as the load does not surpass the maximum engine capacity at that speed. Literature sources (4)(6) state that, if the load demand exceeds this maximum figure, the control system automatically reduces propeller pitch until the load demand equals the power available at that engine speed. Consequently, a constant-speed/variable-load system is employed which produces the nominal power output that is required to achieve the desired propeller speed under average cutter operating conditions (wave height, wind velocity, draft, etc.). Changes in these conditions will increase or decrease the engine power output demand relative to this nominal value, and the engine control mechanism will respond accordingly to maintain constant speed. However, information from the Coast Guard[7] contradicts these sources; presently, propeller pitch does not change unless the control handle is moved. The engines are not protected from overload; consequently, engine speed decreases if overload occurs.

### 4.1.2 WIND Class Icebreakers (WAGB)

The WIND Class Icebreakers employ a diesel-electric drive system in which each of the two constant-pitch propellers is driven by a motor which, in turn, is powered by a pair of engine/generator sets. With this system, propeller shaft speed is independent of engine speed, but is controlled by generator load as shown in Table 4-2.

TABLE 4-2. PARAMETER VALUES FOR ICEBREAKER OPERATING WAGB WESTWIND

| Mode | Shaft RPM | Engine RPM | Gen. Volt | Gen. Amp | Gen. HP |
|---|---|---|---|---|---|
| 1/3 | 38 | 395 | 310 | 100- 150 | 42- 63 |
| 2/3 | 80 | 430 | 650-675 | 300- 500 | 263- 456 |
| Standard | 105 | 460 | 850-900 | 600- 700 | 688- 850 |
| Full | 125-130 | 460 | 900-950 | 1200-1400 | 1458-1798 |
| Flank | 125-130 | 460 | 900-950 | 1800-2000 | 2187-2565 |

## 4.2 DUTY CYCLE RECORDING EQUIPMENT

The time of operation in each handle position for these cutters was acquired by two methods; first, engine room logs which contained a record of all bell order (operating mode) changes made by engine room personnel were analyzed to extract any duty cycle data they might contain. However, this approach was applicable only to the WHEC class since the other two classes did not keep such a log. The second method, in which the ships were instrumented with recorders to log total operating time and time spent in each throttle position for each engine, was employed for all three classes.

The duty cycle recorder system instrumentation utilized signals from the engine/propeller control system to record throttle position and operating time. However, due to differences in the control systems of the three types of cutters, the design of the interface joining the control system to the recorders varied among the classes as outlined below.

### 4.2.1 Medium-Endurance Cutter Instrumentation

The WMEC control system is pneumatic in its operation. Speed and pitch adjustments are accomplished through pressure transmitters which are positioned by cams. For a given handle position, these cams program a particular shaft speed and propeller pitch through air signals to the engine governor and pitch positioner.[6]

---

[7]Telephone conversation with LCDR. D. Reichl, U.S. Coast Guard, June 1980.

The duty cycle recorder system used on these cutters employed a mechanical switching device which was fabricated to fit the engine control camshafts located under the pilot house control console. The switch program was arranged such that the numbered (0 through 8) handle positions activated the recorder channel with the same number, while the "one-half" or in-between positions activated both adjacent channels. A strip chart recorder capable of recording 20 channels of "on/off" events on heat sensitive paper was mounted in the Combat Information Center (CIC) room directly below the control console. Also, two digital run-time meters were installed in the engine room control station to log total individual engine running time.

The interface was connected to the pilot house (bridge) controls. These controls did not function when ship control was transferred to the engine room; as a result, the recording system failed to log this time. The total operating time from the run time meters was compared to the sum of the individual modal times from the strip charts to determine the amount of time actually spent under engine room control.

Additionally, total operating time was needed for the calculations of idling time since the pilot house throttles were left in the "idle" position when (a) engines were indeed idling, (b) engines were under engine room control, (c) engines were secured. Consequently, the charts indicated a large amount of time for the idle position which did not actually involve engine idle operation. The method used to calculate idle time was as follows:

> (engine room meter running time) minus (sum of chart recorder times for "non-idle" conditions) minus (estimate of time spent under engine room control) equals (engine idling time).

Duty cycle data was collected from recorders installed on the medium-endurance cutters DECISIVE, VALIANT, and DURABLE (WMEC's 629, 621, and 628).

### 4.2.2 High-Endurance Cutter Instrumentation

Propeller pitch and engine speed of the WHEC's are regulated by an electronic control system which operates in the same fashion as the pneumatic system described for the WMEC's. Monitoring handle position directly as an indicator of operating mode was impractical in this case. Rather, engine speed was recorded using the voltage output of the shaft tachometer to activate the corresponding channel of a strip chart recorder (one channel per engine) through a voltage comparator. As with the WMEC's, run-time meters logged total individual engine operating time. Idling time was calculated as the difference between total operating time shown on the run-time meters and the sum of "non-idle" operating conditions recorded on the strip chart. Two WHEC's, the HAMILTON and CHASE (nos. 715 and 718), were instrumented in this manner. Additionally, duty cycle data was extracted from the engine room logs of the cutters CHASE and GALLATIN (WHEC 721).

### 4.2.3 Icebreaker Instrumentation

As previously mentioned, the WIND Class Icebreakers employ a diesel-electric drive system as opposed to a diesel/gas turbine arrangement. Since propeller speed is independent of engine speed for this system, it was necessary to record the generator output as well as the engine speed to determine an operating mode. Consequently, four strip chart recorders, one for each engine/generator set, monitored engine speed and generator voltage and amperage. As with the WHEC's, the voltage output of the tachometers was used to determine engine speed. In this case, the strip chart recorders ran continuously so that total operating time and idle time could be extracted directly from the charts. This system was installed on the WESTWIND (WAGB 281).

## 4.3 DATA REDUCTION

Reduction of the duty cycle data taken from the high- and medium-endurance cutters amounted to summing, for each channel, the time that information was recorded by that channel. Total time indicated by a channel corresponded to total operating time in a particular mode. Using the information from the run-time meters installed on each engine, idling time was computed as indicated earlier.

Information from the icebreaker's recording system was analyzed in a similar fashion; however, a correlation was necessary between engine speed and generator amperage and voltage to establish an operating mode. Some of the data from the charts fell between two modes, and it was necessary to establish tolerance bands around the recorded parameters. Thus, the grouping of data was determined by a "go-no go" decision as to whether the operating mode was, for example, Standard or Full. A discussion of these variations and their grouping is included in a later section of this report.

Time-based modal factors were computed for each of the cutters indicating the percentage time spent in each operating mode. This was performed on a chart-to-chart basis (approximately one month running time per chart), as well as on a cumulative basis to provide an assessment of month-to-month changes for each cutter.

## 5. PROPELLER PITCH/EFFICIENCY ANALYSIS

Information was obtained on propeller, cutter, and engine performance of the medium- and high-endurance cutters for the purpose of evaluating the effect of mode changes on fuel consumption and cutter performance. This included propeller diagrams, which relate shaft horsepower to propeller shaft speed throughout the design pitch and speed range, and engine performance maps for the main propulsion units. Since direct-drive propulsion systems were employed, each point on the propeller diagram uniquely determined the engine load and speed conditions. Fuel consumption was computed throughout the range of data available on propeller and engine performance. Also, a cycle composite fuel consumption (the average fuel usage rate based on a pitch schedule and weighted by the time-based modal factors) was developed.

Two discrepancies arose when working with the high-endurance cutters. First, it was found that two different propellers were in use; earlier cutters (WHEC's 715 through 718) were equipped with propellers manufactured by Propulsion Systems, Inc., while the remaining cutters (WHEC 719 - WHEC 726) used an Escher-Wyss design. Consequently, it was necessary to obtain the propeller diagrams for both makes and then perform the analysis for each case. Second, these ships were reported to be approximately 10% over the design weight, which resulted in increased ship draft and increased hull resistance. It was thus necessary to correct propeller diagrams for both configurations to account for the added horsepower necessary to propel the ship at a given speed. The correction was provided by Professors William Vorus and M. G. Parsons of the University of Michigan; a detailed report is included in Appendix A.

Recommendations for changes in the pitch program of the WMEC's and WHEC's for improved fuel consumption were based on data from the propeller diagrams and engine fuel consumption maps; these data were analyzed by two methods. First, alterations in the engine speed/propeller pitch combinations were restricted to produce the same vessel speed in each mode as the existing schedule; second, changes were made without this restriction.

Additionally, single-engine operation of the high-endurance cutters was considered. The principle behind this type of operation is as follows: At slow ship speeds, the main diesel engines are forced to operate at slow speed-low load conditions, resulting in high brake specific fuel consumption (BSFC). Transferring propulsion to a single engine would shift the operating point to a higher speed-load condition at the same ship speed, thus reducing BSFC but increasing the total fuel consumption of that engine. Single-engine operation would then be advantageous if total fuel consumption was less than the total for two-engine operation.

Single-engine operation has, in fact, been used by WHEC's, although not specifically for a reduction in fuel consumption and primarily at the discretion of the commanding officer. The usual procedure was to allow the unused propeller to freewheel at full-ahead pitch, disengaging it after it had been in operation. The propeller continued to rotate, but it was reported that, if the ship slowed to the point where the free propeller stopped, it would not start to rotate once the ship got underway again. WHEC's were reputed to achieve 10.5 knots on one screw at an engine speed of 660 RPM, but at unknown pitch.

The propeller diagrams for both Escher-Wyss and PSI designs were modified for single-engine operation with considerations for a trailing (rotating) and a locked propeller shaft (Appendix A). Fuel consumption data were analyzed throughout the permissible operating range to determine if, and when, single engine operation was feasible.

# 6. DISCUSSION OF RESULTS

## 6.1 MEDIUM-ENDURANCE CUTTER (WMEC) DUTY CYCLE DATA

The data from the duty cycle recorder systems for the medium-endurance cutters VALIANT, DURABLE, and DECISIVE are presented in Tables 6-1 through 6-3. While analyzing the charts from the recorders, it was observed that all of the WMEC's showed only minor redistribution of the percentage time spent in each operating position from month to month, though there were monthly variations in total running time.

In general, both engines of a ship operated primarily in the same range of throttle positions, but the individual modal percentages varied somewhat between the two engines of each vessel; this situation could have been due to either an imbalance in engine power output or because of the fact that the WMEC's frequently operated on one engine. The DURABLE and the DECISIVE, respectively, logged 23% more time on the port engine; the times for the VALIANT differed by only 4%. Additionally, the most commonly used throttle positions varied among the ships. For example, the DECISIVE operated principally in positions 3 to 4 1/2, while the DURABLE employed positions 6 to 6 1/2 most frequently (Tables 6-2 and 6-3). The primary throttle positions employed by the cutters and the time spent in that range are summarized in Table 6-4.

A set of time-based modal factors was generated for the WMEC's by summing the operating time for both engines in a particular operating mode and computing the percentage of total operating time that this represented. These results are summarized in Table 6-5. The modal weighting factors indicate that the vast majority of the combined operating time (78%) was spent in handle positions 3 to 6 1/2 and half of the remainder was spent at Idle. Handle positions 8 and 1 to 1 1/2 were, for all practical purposes, unused.

TABLE 6-1. DUTY CYCLE MODES AND TIMES -- WMEC VALIANT

January 1 - September 5, 1976

| Throttle Position | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| 0 (Idle) | 91.1 | 10 | 79.0 | 8 |
| 1 to 1 1/2 | 1.4 | 0 | 2.7 | 0 |
| 2 to 2 1/2 | 48.4 | 5 | 47.9 | 5 |
| 3 to 3 1/2 | 127.2 | 14 | 110.9 | 12 |
| 4 to 4 1/2 | 227.8 | 24 | 281.5 | 29 |
| 5 to 5 1/2 | 52.1 | 6 | 111.2 | 12 |
| 6 to 6 1/2 | 311.2 | 34 | 246.5 | 26 |
| 7 to 7 1/2 | 62.8 | 7 | 64.5 | 7 |
| 8 | Nil | 0 | 6.9 | 1 |
| Totals | 992.0 | 100 | 951.9 | 100 |

TABLE 6-2. DUTY CYCLE MODES AND TIMES -- WMEC DECISIVE

October 19, 1976 - June 28, 1977

| Throttle Position | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| 0 (Idle) | 116.9 | 11 | 121.6 | 9 |
| 1 to 1 1/2 | 28.6 | 3 | 15.9 | 1 |
| 2 to 2 1/2 | 108.4 | 10 | 49.7 | 3 |
| 3 to 3 1/2 | 381.1 | 35 | 371.8 | 27 |
| 4 to 4 1/2 | 252.2 | 23 | 480.4 | 34 |
| 5 to 5 1/2 | 121.8 | 11 | 262.6 | 19 |
| 6 to 6 1/2 | 72.1 | 6 | 95.8 | 7 |
| 7 to 7 1/2 | 6.4 | 1 | 1.3 | 0 |
| 8 | 0.5 | 0 | Nil | 0 |
| Totals | 1088.0 | 100 | 1399.1 | 100 |

TABLE 6-3. DUTY CYCLE MODES AND TIMES -- WMEC DURABLE

April 11 - September 1, 1976

| Throttle Position | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| 0 (Idle) | 122.7 | 16 | 93.6 | 15 |
| 1 to 1 1/2 | 2.4 | 0 | 6.0 | 1 |
| 2 to 2 1/2 | 22.6 | 3 | 24.6 | 4 |
| 3 to 3 1/2 | 50.0 | 6 | 38.0 | 6 |
| 4 to 4 1/2 | 57.8 | 7 | 45.3 | 7 |
| 5 to 5 1/2 | 85.3 | 11 | 104.3 | 16 |
| 6 to 6 1/2 | 258.9 | 32 | 328.8 | 51 |
| 7 to 7 1/2 | 191.2 | 25 | 1.0 | 0 |
| 8 | Nil | 0 | Nil | 0 |
| Totals | 790.9 | 100 | 641.6 | 100 |

TABLE 6-4. PRINCIPAL THROTTLE POSITION USE -- WMEC

| Ship | Average Monthly Operating Time | Throttle Position | % TIME | |
|---|---|---|---|---|
| | | | Port | Starboard |
| | (Port-Starboard) | | | |
| VALIANT | (115-120) hr/mo | 3 to 6 1/2 | 78% | 79% |
| DURABLE | (160-130) hr/mo | 4 to 6 1/2 | 50% | 74% |
| DECISIVE | (135-175) hr/mo | 3 to 5 1/2 | 69% | 80% |

TABLE 6-5. AVERAGE TIME-BASED MODAL WEIGHTING FACTORS -- WMEC

| Throttle Position | Valiant | | Durable | | Decisive | | Total | Modal Weighting Factor |
|---|---|---|---|---|---|---|---|---|
| | Port (hrs) | Stbd. (hrs) | Port (hrs) | Stbd. (hrs) | Port (hrs) | Stbd. (hrs) | (hrs) | |
| 0 (Idle) | 91.1 | 79.0 | 122.7 | 93.6 | 116.9 | 121.6 | 624.9 | 0.11 |
| 1 to 1 1/2 | 1.4 | 2.7 | 2.4 | 6.0 | 28.6 | 15.9 | 57.0 | 0.01 |
| 2 to 2 1/2 | 48.4 | 47.9 | 22.6 | 24.6 | 108.4 | 49.7 | 302.0 | 0.05 |
| 3 to 3 1/2 | 127.2 | 110.9 | 50.0 | 38.0 | 381.1 | 371.8 | 1079.0 | 0.19 |
| 4 to 4 1/2 | 227.8 | 281.5 | 57.8 | 45.3 | 252.2 | 480.4 | 1345.0 | 0.23 |
| 5 to 5 1/2 | 52.1 | 111.2 | 85.3 | 104.3 | 121.8 | 262.6 | 737.3 | 0.13 |
| 6 to 6 1/2 | 311.2 | 246.5 | 258.9 | 328.3 | 72.1 | 95.8 | 1312.8 | 0.23 |
| 7 to 7 1/2 | 62.8 | 64.5 | 191.2 | 1.0 | 6.4 | 1.3 | 327.2 | 0.06 |
| 8 | Nil | 6.9 | Nil | Nil | 0.5 | Nil | 7.4 | Nil |
| Totals | — | — | — | — | — | — | 5792.6 | 1.0 |

## 6.2 HIGH-ENDURANCE CUTTER (WHEC) DUTY CYCLE DATA

The WHEC duty cycle data obtained from the on-board recording system were supplemented by information extracted from engine room logs, which contained a record of bell orders (mode changes) received from the bridge. These records were, however, found to be incomplete or at least ambiguous concerning important details. The findings are summarized below:

a. The bell order record was kept when the engines were on engine room control, but not when pilot house control was used.

b. Recorded bell orders by themselves were insufficient to allow the amount of engine idle time to be determined. However, discrepancies were partially resolved by inspection of the watch officer's log entries for comments concerning the times that an engine was secured (stopped) and restarted.

c. There were instances when the engines were on engine room control, but there occurred a rapid series of bell orders from the bridge. The analysis of such a situation adds greatly to the total analytical time, yet adds little useful information since the operating time involved is usually short compared to the total engine operating time. Therefore, these situations were skipped over without significantly degrading the data.

The actual duty cycle data which were extracted from the engine room logs of the WHEC's CHASE and GALLATIN are shown in Tables 6-6 and 6-7. In general, the distribution of time between engine room control and pilot house control, and among the various engine modes, was relatively constant even though total monthly operating time varied greatly. The majority (80-85%) of the operating time was spread over 1/3, 2/3, and Standard modes, with the Standard condition receiving the higher use. Idle time was usually less than 10% of the total, while the combined operating time at Flank and Full was usually less than 10%. A summary of the combined log book data is presented in Table 6-8, which confirms the general remarks given here. During the 10-month period studied, each engine operated an average of 261 hours per month, which corresponds to about eleven (11) days per month, a time utilization factor of approximately 36%. Based on maximum engine power output of 3600 brake horsepower at full speed, and using the average percentages for the combined data, a power utilization factor of 46.0% was calculated for the WHEC main diesel engines. A cycle composite brake specific fuel consumption (BSFC) of 0.397 pounds per brake horsepower-hour was computed based on the engine manufacturer's published BSFC values for each operating mode.

The duty cycle recording system results for the WHEC's CHASE and HAMILTON are shown in Table 6-9. Data from the CHASE followed essentially the same monthly pattern as did the log book data, but a slight deviation from log book data was noted as engine operation was primarily at 1/3 and 2/3, while Standard condition occupied most of the remaining portion. Operation at Full was slight, and little or no time was recorded at Idle and Flank speeds. Average monthly operation was almost 300 hours per engine. Total accumulated hours for the two engines were within two percent, and the percentage time spent in each mode by each engine was very nearly equal.

In contrast to the CHASE, the HAMILTON accumulated a significant amount of Flank operating mode (42% to 45%). It is possible that this type of operation may have been peculiar to a specific mission and, as such, is not indicative of normal operating conditions. Other patterns are similar to the CHASE in that percentage time in each mode for each engine and total accumulated time for the two engines was almost equal. However, total recorded operating time for the six-month data acquisition period was less than 300 hours; this very low utilization is due to the fact that the HAMILTON was in port for several months for maintenance. After the ship returned to duty, problems arose with the instrumentation so that little usable data was returned to SwRI for analysis.

The time-based modal factors for the high-endurance cutters were computed from information taken from the duty cycle recorders on-board the CHASE. This was deemed to be the most extensive and most accurate data available. The resulting factors are shown in Table 6-10 and reflect the trends described previously for the CHASE.

TABLE 6-6. LOG BOOK DUTY CYCLE DATA - WHEC CHASE

| Period Covered | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| AUGUST 1975 | | | | |
| Total Operating Time | 403.7 | 100 | 390.7 | 100 |
| Engine Room Control | 278.5 | 69 | 265.5 | 68 |
| Pilot House Control | 125.2 | 31 | 125.2 | 32 |
| Engine Mode | | | | |
| Idle | 20.2 | 7 | 25.7 | 10 |
| 1/3 | 89.5 | 32 | 80.0 | 30 |
| 2/3 | 27.3 | 10 | 26.4 | 10 |
| Standard | 133.1 | 48 | 125.0 | 47 |
| Full | 8.4 | 3 | 8.4 | 3 |
| Flank | Nil | 0 | Nil | 0 |
| Totals | 278.5 | 100 | 265.5 | 100 |
| OCTOBER 1975 | | | | |
| Total Operating Time | 183.5 | 100 | 187.6 | 100 |
| Engine Room Control | 156.0 | 85 | 160.1 | 85 |
| Pilot House Control | 27.5 | 15 | 27.5 | 15 |
| Engine Mode | | | | |
| Idle | 17.5 | 11 | 16.6 | 10 |
| 1/3 | 30.1 | 20 | 33.0 | 21 |
| 2/3 | 29.6 | 19 | 30.8 | 19 |
| Standard | 78.5 | 50 | 79.4 | 50 |
| Full | 0.3 | 0 | 0.3 | 0 |
| Flank | Nil | 0 | Nil | 0 |
| Totals | 156.0 | 100 | 160.1 | 100 |
| NOVEMBER 1975 | | | | |
| Total Operating Time | 194.8 | 100 | 195.1 | 100 |
| Engine Room Control | 164.1 | 84 | 164.4 | 84 |
| Pilot House Control | 30.7 | 16 | 30.7 | 16 |
| Engine Mode | | | | |
| Idle | 17.2 | 10 | 15.0 | 9 |
| 1/3 | 13.8 | 8 | 16.8 | 10 |
| 2/3 | 12.6 | 8 | 11.0 | 6 |
| Standard | 116.9 | 71 | 118.0 | 72 |
| Full | 1.0 | 1 | 1.0 | 1 |
| Flank | 2.6 | 2 | 2.6 | 2 |
| Totals | 165.1 | 100 | 164.4 | 100 |

TABLE 6-7. LOG BOOK DUTY CYCLE DATA - WHEC GALLATIN

| Period Covered | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| SEPTEMBER 1975 | | | | |
| Total Operating Time | 186.0 | 100 | 215.6 | 100 |
| Engine Room Control | 171.6 | 92 | 201.2 | 93 |
| Pilot House Control | 14.4 | 8 | 14.4 | 8 |
| Engine Mode | | | | |
| Idle | 16.8 | 10 | 14.1 | 7 |
| 1/3 | 34.0 | 20 | 36.8 | 18 |
| 2/3 | 32.2 | 19 | 55.4 | 28 |
| Standard | 68.4 | 40 | 74.8 | 37 |
| Full | 15.5 | 9 | 15.4 | 8 |
| Flank | 4.7 | 2 | 4.7 | 2 |
| Totals | 171.6 | 100 | 201.2 | 100 |
| OCTOBER 1975 | | | | |
| Total Operating Time | 301.5 | 100 | 351.7 | 100 |
| Engine Room Control | 287.0 | 95 | 337.2 | 96 |
| Pilot House Control | 14.5 | 5 | 14.5 | 4 |
| Engine Mode | | | | |
| Idle | 13.1 | 4 | 16.4 | 5 |
| 1/3 | 36.2 | 13 | 17.6 | 5 |
| 2/3 | 79.5 | 28 | 70.4 | 21 |
| Standard | 135.1 | 47 | 209.8 | 62 |
| Full | 19.7 | 7 | 19.6 | 6 |
| Flank | 3.4 | 1 | 3.4 | 1 |
| Totals | 287.0 | 100 | 337.2 | 100 |

TABLE 6-8a. SUMMARY OF LOG BOOK DUTY CYCLE DATA FOR WHEC -- FIVE CUTTER-MONTHS OF OPERATION

| | Port Engine Average | | Starboard Engine Average | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| Total Operating Time | 253.9 | 100 | 268.1 | 100 |
| Engine Room Control | 211.4 | 83 | 225.7 | 84 |
| Pilot House Control | 42.5 | 17 | 42.5 | 16 |
| Engine Mode | | | | |
| Idle | 17.0 | 8 | 17.6 | 8 |
| 1/3 | 40.7 | 20 | 36.8 | 16 |
| 2/3 | 36.2 | 17 | 38.8 | 17 |
| Standard | 106.4 | 50 | 121.4 | 54 |
| Full | 9.0 | 4 | 9.0 | 4 |
| Flank | 2.1 | 1 | 2.1 | 1 |
| Totals | 211.4 | 100 | 225.7 | 100 |

TABLE 6-8b. OVERALL AVERAGE PER MONTH

| | Total Operation for 10 Engine-Months | |
|---|---|---|
| | Hours | % |
| Total Operating Time | 261.0 | 100 |
| Engine Room Control | 218.5 | 84 |
| Pilot House Control | 42.5 | 16 |
| Engine Mode | | |
| Idle | 17.3 | 8 |
| 1/3 | 38.7 | 18 |
| 2/3 | 37.5 | 17 |
| Standard | 113.9 | 43 |
| Full | 9.0 | 4 |
| Flank | 2.1 | 1 |
| Totals | 218.5 | 100 |

TABLE 6-9a. DUTY CYCLE MODES AND TIMES -- WHEC CHASE TAKEN FROM DUTY CYCLE RECORDER SYSTEM

March 15 - August 20, 1976

| Engine Mode | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| Idle | 0.1 | 0 | 0.3 | 0 |
| 1/3 | 497.6 | 33 | 462.9 | 32 |
| 2/3 | 550.8 | 37 | 555.0 | 38 |
| Standard | 334.3 | 23 | 334.6 | 23 |
| Full | 105.9 | 7 | 104.9 | 7 |
| Flank | Nil | 0 | Nil | 0 |
| Totals | 1488.7 | 100 | 1457.7 | 100 |

TABLE 6-9b. DUTY CYCLE MODES AND TIMES -- WHEC HAMILTON TAKEN FROM DUTY CYCLE RECORDER SYSTEM

October 19, 1976 - April 15, 1977

| Engine Mode | Port Engine | | Starboard Engine | |
|---|---|---|---|---|
| | Hours | % | Hours | % |
| Idle | 2.4 | 1 | 0.8 | 0 |
| 1/3 | 34.3 | 12 | 20.1 | 8 |
| 2/3 | 54.2 | 19 | 49.0 | 19 |
| Standard | 41.3 | 15 | 45.5 | 17 |
| Full | 29.8 | 11 | 30.2 | 11 |
| Flank | 120.0 | 42 | 117.4 | 45 |
| Totals | 282.0 | 100 | 263.0 | 100 |

TABLE 6-10. WMEC TIME-BASED MODAL WEIGHTING FACTORS

| Engine Mode | % of Total Operating Time |
|---|---|
| Idle | 0 |
| 1/3 | 32.5 |
| 2/3 | 37.5 |
| Standard | 23 |
| Full | 7 |
| Flank | 0 |
| Total | 100 |

## 6.3 WIND CLASS ICEBREAKER (WAGB) DUTY CYCLE DATA

Duty cycle data from the Icebreaker WESTWIND are shown in Table 6-11. No data were available for engine 2A due to a recorder problem, which was compounded when the 2A generator failed. It should be pointed out at this time that the WESTWIND was damaged and underwent drydock repairs during the icebreaking season; this precluded obtaining data during such operation. The project was terminated before the next icebreaking season, so that the data given here represents operation in open-water conditions during a North Sea cruise.

From Table 6-11, it can be seen that operating time and percentages varied somewhat among the modes for the three engines; these variations are believed to occur for three reasons. First, some of the data from the recorder charts fell between two modes. As a result, the data grouping was determined by establishing arbitrary tolerance bands around the recorded parameters, which introduced a degree of uncertainty in the analysis. The second factor causing time variations among the modes was the desire to keep the two propeller shafts rotating at the same designated speed and the engines producing equal power for each shaft. Adjustment of individual engine operating modes was required to obtain this balanced condition with the diesel-electric propulsion system; therefore, engines on the same shaft can be compared, but not engines on opposite shafts.[7] Third, in an effort to reduce fuel consumption, the icebreaker regularly operated on just two of the four engine/generator sets, using one set per propeller. This increased the load on each engine and caused them to operate at a lower BSFC. Total operating time was balanced by alternating the two engines used in this manner.

The data indicated that a significant amount of time was spent in the Full and Flank modes. This was probably due to the fact that the icebreaker was on an extended cruise in the North Atlantic and was not engaged in any icebreaking activity. The 2/3 mode received only minor use, and the remainder of the operating time was evenly distributed among idle, 1/3, and Standard. Since the data do not include icebreaking activities and represent a relatively short operating period for a single cutter, these observations cannot be used to generalize icebreaker operation.

## 6.4 MEDIUM-ENDURANCE CUTTER PROPELLER PITCH/ENGINE PERFORMANCE ANALYSIS

Fuel consumption of the WMEC's (in terms of pounds per hour per engine and gallons per nautical mile per engine) and the percentage increase in each quantity from the minimum value for a given ship speed were calculated for points throughout the cutter speed and propeller pitch ranges. Basic data and results of these computations are presented in Appendix B. These engine fuel consumption figures have been mapped onto the propeller diagram in Figure 6-1 as a function of cutter speed and propeller pitch.

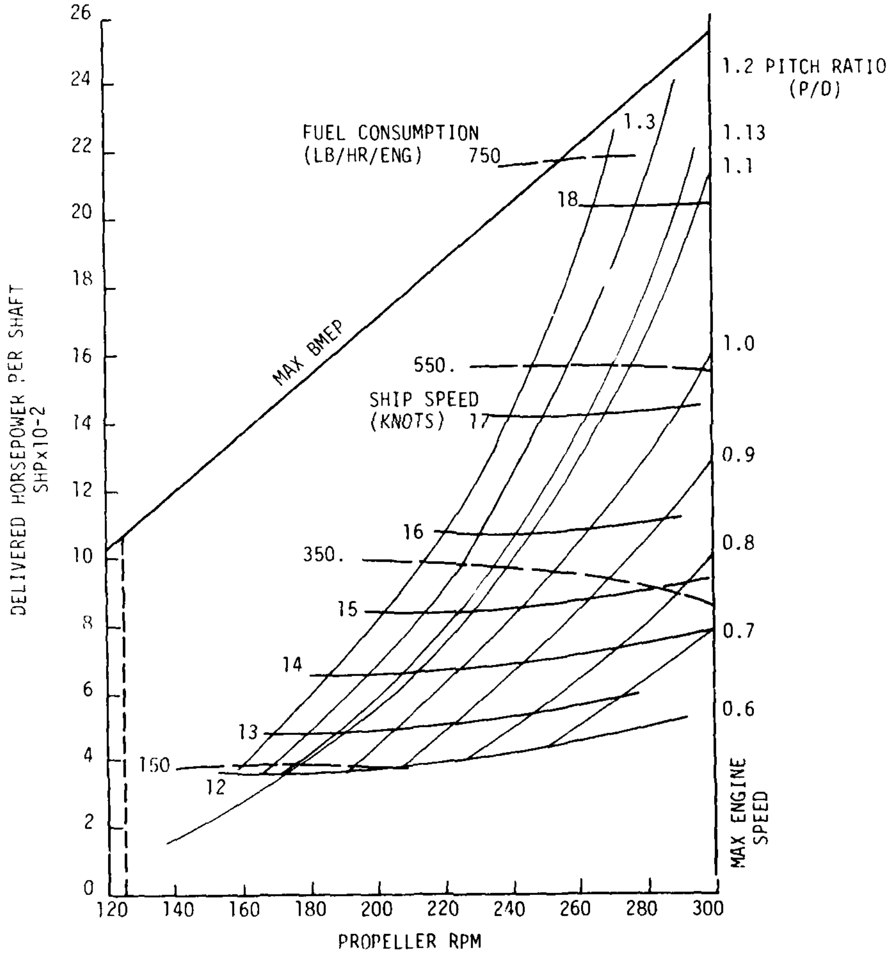


FIGURE 6-1. WMEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION

TABLE 6-11. DUTY CYCLE MODES AND TIMES -- WAGB WESTWIND

March 18

| Engine Mode | Engine 1A | | Engine 2A | | Engine 1B | | Engine 2B | |
|---|---|---|---|---|---|---|---|---|
| | Hours | % | Hours | % | Hours | % | Hours | % |
| Idle | 59.3 | 10 | —— | —— | 69.9 | 11 | 76.0 | 12 |
| 1/3 | 19.3 | 4 | —— | —— | 73.7 | 13 | 63.0 | 10 |
| 2/3 | 32.3 | 5 | —— | —— | 35.3 | 6 | 23.2 | 4 |
| Standard | 50.2 | 9 | —— | —— | 89.1 | 16 | 101.2 | 17 |
| Full | 237.9 | 40 | —— | —— | 132.2 | 23 | 191.6 | 32 |
| Flank | 190.2 | 32 | —— | —— | 176.7 | 31 | 153.0 | 25 |
| Totals | 589.2 | 100 | —— | —— | 571.9 | 100 | 608.0 | 100 |

Several trends in the WMEC data are evident. First, a small increase in ship speed required a large increase in fuel consumption, regardless of the pitch ratio. Second, for any given ship speed, as the pitch ratio increased, fuel consumption decreased until it reached a minimum value at the two or three highest pitch ratios. Finally, fuel consumption became much more sensitive to changes in pitch as ship speed was reduced. Even though data were not available for low ship speeds, it was assumed that these trends extended into this region.

Referring to the propeller diagram (Figure 6-1) and to Figures 6-2 and 6-3, fuel consumption savings are possible for the WMEC without sacrificing ship speed. Movement of the operating point within the envelope bounded above by a constant fuel rate and below by a constant ship speed line, and which intersects at the original operating point, would produce a reduction in fuel usage as well as a possible increase in cutter speed. For example, the operating point Figure 6-1 defined by

285 SRPM

15 Knots

0.85 Pitch Ratio

350 lb/hr/eng Fuel Consumption

could be shifted to the left along the constant ship speed line of 15 knots to a higher pitch ratio of 1.3, thus reducing fuel consumption by approximately 50 lb/hr/eng. However, the most dramatic decrease in fuel consumption results from shifting an operating point vertically down the propeller diagram by holding engine speed constant and reducing the propeller pitch. Unfortunately, this also results in a significant penalty in ship speed.

A cycle composite fuel consumption value was calculated for the medium-endurance cutters based upon the parameters given above and the WMEC time-based modal factors; it is presented in Table 6.12a. Also, a second optimized cycle composite fuel consumption (Table 6.12b) was computed according to the following assumptions. First, operating mode changes are made at constant ship speed. Second, for all ship speeds, an increase in pitch reduces fuel consumption throughout the operating range. Last, the maximum design pitch, as shown on the propeller diagram, can be obtained during diesel engine operation in the region where maximum engine torque or brake mean effective pressure (BMEP) is not exceeded. Mode changes were limited to the constant ship speed condition since it was believed that, when a specific mode was called for, a certain cutter speed was actually desired. Further, it is already known that fuel consumption savings are possible by operating at slower speed conditions.

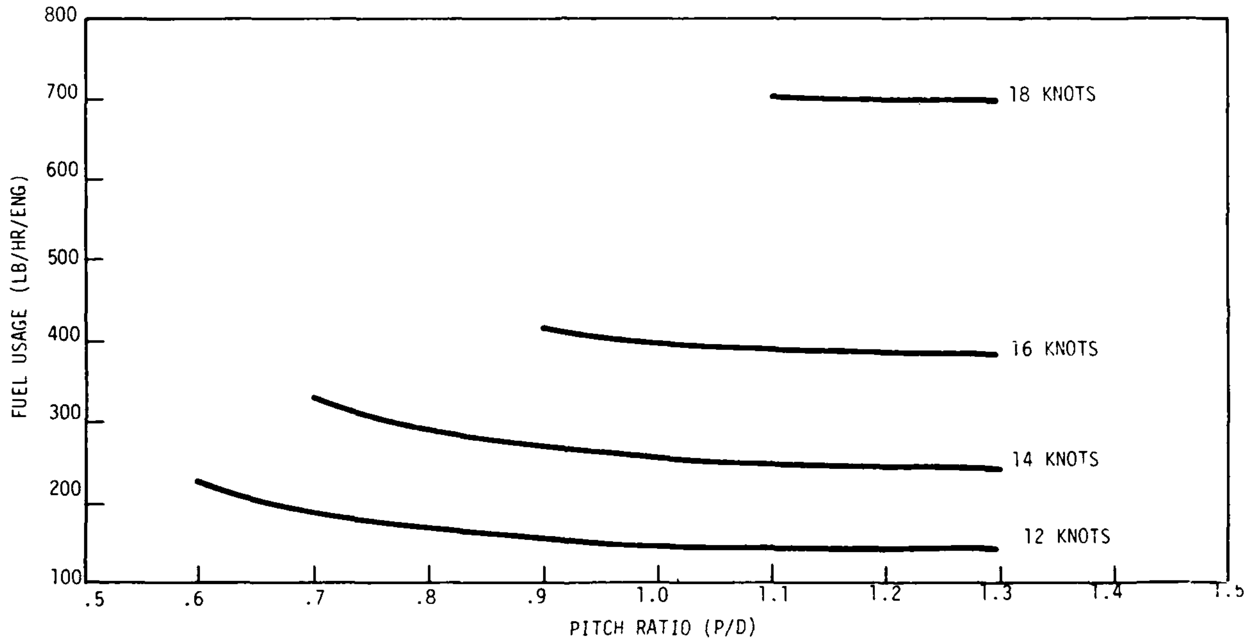


FIGURE 6-2. EFFECT OF PITCH RATIO ON FUEL CONSUMPTION -- USCG 210B WMEC

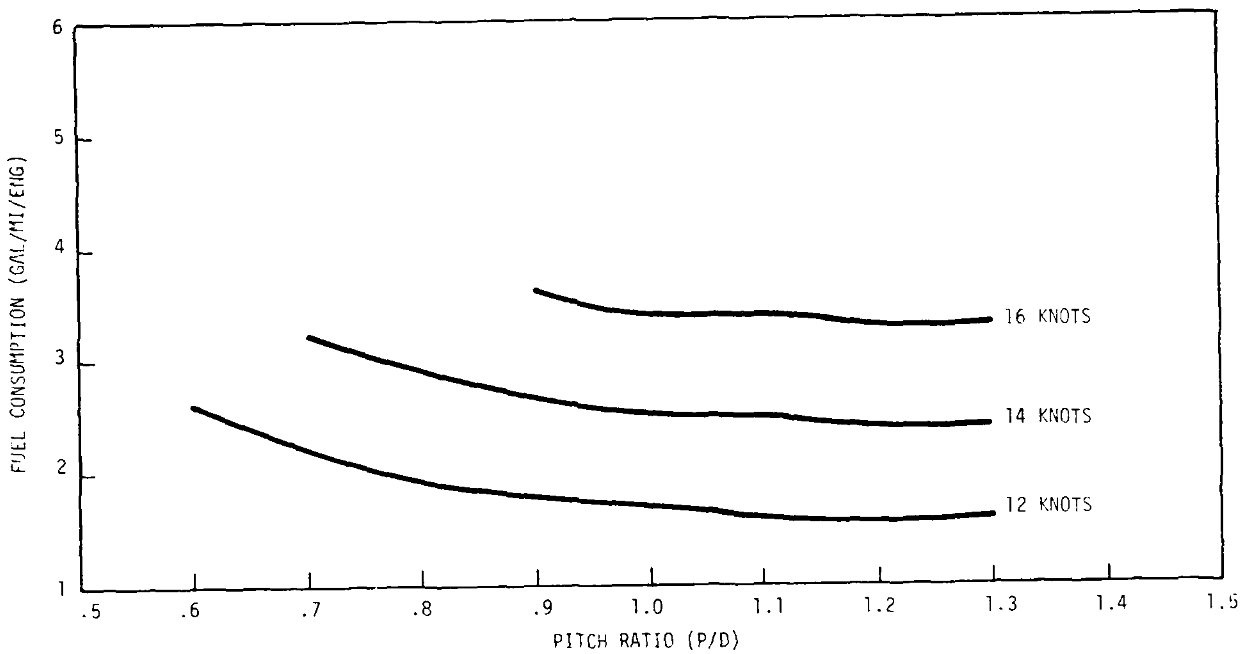


FIGURE 6-3. EFFECT OF PITCH RATIO ON FUEL CONSUMPTION -- USCG 210B WMEC

TABLE 6-12a. CYCLE COMPOSITE FUEL CONSUMPTION -- 210B WMEC

| Throttle Position | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | BSFC lb/BHP-hr | Fuel Consumption lb/hr/eng | Fuel Consumption gal/mi/eng | Weighted Fuel Consumption lb/hr/eng | Weighted Fuel Consumption gal/mi/eng. |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0.11 | 0 | 480 | - | - | 36 | - | 4.0 | - |
| 1 | 1.6 | 0.01 | .23 | 480 | 2 | - | 36 | 3 | 0.4 | .03 |
| 2 | 3.3 | 0.05 | .48 | 480 | 3.3 | .68 | 36 | 1.2 | 1.5 | .06 |
| 3 | 5 | 0.19 | .71 | 480 | 5 | .45 | 36 | 1.0 | 6.8 | .19 |
| 4 | 8 | 0.23 | .95 | 525 | 8.8 | .43 | 60.2 | 1.0 | 13.8 | .24 |
| 5 | 13.2 | 0.13 | 1.13 | 640 | 31.9 | .380 | 193.8 | 2.1 | 25.2 | .27 |
| 6 | 15 | 0.23 | 1.13 | 750 | 51.6 | .365 | 301.1 | 2.8 | 69.3 | .64 |
| 7 | 17.1 | 0.06 | 1.13 | 875 | 90 | .354 | 510.4 | 4.2 | 30.6 | .25 |
| 8 | 18.3 | 0 | 1.13 | 1000 | 144 | .342 | 787 | 6.0 | 0 | 0 |
| Totals | — | 1.0 | — | — | — | — | — | — | 151.6 | 1.68 |

TABLE 6-12b. OPTIMIZED CYCLE COMPOSITE FUEL CONSUMPTION -- 210B WMEC

| Throttle Position | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | BSFC lb/BHP/hr | Fuel Consumption lb/hr/eng | Fuel Consumption gal/mi/eng | Weighted Fuel Consumption lb/hr/eng | Weighted Fuel Consumption gal/mi/eng |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0.11 | 0 | 480 | 0 | - | 36 | - | 4.0 | - |
| 1 | 1.6 | 0.01 | .23 | 480 | 2 | - | 36 | 3 | 0.4 | .03 |
| 2 | 3.3 | 0.05 | .48 | 480 | 3.3 | .68 | 36 | 1.2 | 1.5 | .06 |
| 3 | 5 | 0.19 | .71 | 480 | 5 | .45 | 36 | 1.0 | 6.8 | .19 |
| 4 | 8 | 0.23 | 1.05 | 480 | 8.8 | .43 | 60.2 | 1.0 | 13.8 | .24 |
| 5 | 13.2 | 0.13 | 1.3 | 557 | 31.6 | .375 | 189.4 | 2.0 | 24.6 | .26 |
| 6 | 15 | 0.23 | 1.3 | 677 | 51.3 | .364 | 298.5 | 2.8 | 68.7 | .64 |
| 7 | 17.1 | 0.06 | 1.3 | 800 | 89.4 | .352 | 503.3 | 4.2 | 30.2 | .25 |
| 8 | 18.3 | 0 | 1.3 | 933 | 143.8 | .342 | 787 | 6.0 | 0 | 0 |
| Totals | — | 1.0 | — | — | — | — | — | — | 150.0 | 1.67 |

The final assumption in the set may not be true; the WMEC may not be able to achieve maximum pitch with diesel engine operation. At present, the WMEC's operate at a maximum pitch ratio of 1.13, well below the design specification value of 1.3. The maximum design pitch specification was the value at which a physical stop was placed in the amount of blade rotation; it was not meant to be an operating point and is not an indicator of the maximum pitch that the engines can handle. Also, these propellers were designed for the 210A's gas turbine operation.[7] The diesel engines may not be able to supply the power necessary to turn the propellers at higher pitch and reduced rotational speed. Referring to the propeller diagram, as pitch increases at constant ship speed there is actually a slight reduction in the required shaft horsepower, but a large decrease in shaft speed. Consequently, the engines are forced to produce nearly the same power output at a considerably reduced engine speed. Determination of the actual maximum usable pitch would require cutter testing throughout the cutter's speed range. Therefore, the actual and the optimum cycle composite fuel consumption figures represent extremes, and any improvement in fuel consumption is expected to lie between the values given.

The resulting decrease in fuel consumption through optimization of the pitch schedule amounted to only one percent for the WMEC's, as shown in Table 6.12b. As previously observed, at the two or three highest pitch settings fuel consumption was at an essentially constant minimum value. Since operation was either in or very near to this region, only slight benefits were gained solely by increasing pitch and maintaining ship speed. Larger decreases in the cycle composite fuel consumption were possible, but only at the sacrifice of cutter speed (moving an operating point vertically down the propeller diagram). A more practical solution would be to adopt slower ship speed operating practices than to alter the pitch schedule.

## 6.5 HIGH-ENDURANCE CUTTER PROPELLER PITCH/ENGINE PERFORMANCE ANALYSIS

### 6.5.1 Normal (Two-Propeller) Operation

Fuel consumption calculations for the high-endurance cutters were handled in a manner identical to the medium-endurance cutters. Again, these calculations should be looked upon as an approximation of the actual fuel consumption because of the accuracy of the available data. The propeller diagram which relates propeller pitch and speed to ship speed is a theoretical estimate of propeller performance used for design purposes; as such, it may not be an accurate assessment of actual cutter performance. Comparing the propeller diagrams (Figures 6-6 and 6-7) to available WHEC performance data (shown in Table 6-13), significant differences were found. The performance data indicates that ships are operating more efficiently than the propeller diagrams predict because either the propellers are more efficient than design data indicates, or the ships have much less resistance than shown on the resistance curve. Either the corrected propeller diagram is in error, in which case the source of error is either the original Escher-Wyss propeller diagram or the resistance curve (see report in Appendix A), or the performance data in Table 6-13 are wrong. Accurate WHEC performance data must be obtained to clarify the discrepancy.

TABLE 6-13. WHEC PERFORMANCE DATA TAKEN FROM SHIP INSTRUMENTATION

| Pitch Ratio (P/d) | Shaft RPM | Ship Speed (Knots) |
|---|---|---|
| 0.5 | 75 | 5 |
| 1.0 | 75 | 9.8 - 10 |
| 1.0 | 120 | 15 |
| 1.0 | 135 | 16.5 |
| 1.0 | 150 | 17.8 - 18.2 |

Due to the lack of accurate data at slow ship speeds (less than 100 knots) an approximation was made of low-speed fuel consumption. Even though the total fuel consumption in this region is not a major significance, a small change in the operating condition produces a large change in the weighted or cycle composite fuel consumption.

Despite the above discrepancies, the data are of value in evaluating relative changes in cutter operating procedures, but should not be interpreted as an absolute-value estimate of ship fuel consumption. The tabulated fuel consumption figures are presented in Appendix B and summarized in Figures 6-4 and 6-5. Fuel consumption data plotted on the propeller diagram facilitated the analysis of pitch schedule alterations (Figures 6-6 and 6-7). In this regard, the trends observed with the WMEC's also pertained to the WHEC's due to the similarity of the propeller diagrams. Small increases in ship speed required a large increase in fuel consumption, and as pitch ratio increased at a given ship speed, fuel consumption decreased such that a reduction in fuel consumption was possible without sacrificing cutter performance. Alternately, decreasing shaft horsepower (moving vertically down the propeller diagram) resulted in the most significant fuel conservation, but also decreased ship speed.

Cycle composite fuel consumption calculations (Tables 6-14 and 6-15), which were based on the assumptions used for the WMEC's, indicated that fuel savings were possible only in two modes (Standard and Full) when pitch schedule alterations were limited to constant ship speed in each mode. The operating modes 2/3, 1/3, and Idle are at the engine idle speed, and any increase in pitch would result in increased ship speed. The remaining condition, Flank, which represents the non-functional handle positions above eighth position, had a modal weighting factor of zero and did not contribute to the cycle composite fuel consumption.

The resulting decrease in fuel usage was 2.4% and 12% for ships equipped with PSI and Escher-Wyss propellers, respectively. It was assumed that a maximum pitch ratio of 1.4 could be attained in the Standard and Full modes. This is a substantial increase from the maximum pitch ratio of 1.0 which is presently employed, and the ships may, in fact, be unable to achieve this setting. Based on the fuel consumption figures, it appears that the pitch schedule could be re-programmed for minimum fuel consumption throughout the operating range by utilizing the maximum attainable pitch at each engine speed. It is conceivable that the maximum design pitch of 1.4 cannot be obtained at some engine speeds and that the maximum usable pitch may vary throughout the engine speed range. A hypothetical pitch schedule which assumes a maximum usable pitch of 1.4 would consist of three segments when drawn on the propeller diagram (Figures 6-8 and 6-9). First, the pitch schedule would progress vertically up the constant engine idle speed line until a pitch ratio of 1.4 was encountered. Second, the point would move up the 1.4 pitch-ratio line to the intersection with maximum BMEP. The final segment would then consist of the maximum BMEP line up to rated engine speed and load.

It should be pointed out that, at present, ships equipped with Escher-Wyss propellers consume approximately 14% less fuel on a cycle composite basis than those equipped with PSI props. As was mentioned in the propeller diagram correction report (Appendix A), the PSI propeller has a lower efficiency relative to the Escher-Wyss. This also accounts for the small decrease in cycle composite fuel consumption available with the PSI design when pitch is increased at constant ship speed.

### 6.5.2 Single-Engine Operation

Single-engine operation fuel consumption data were extracted from the propeller diagrams and the engine performance map, and are included in Appendix C. This analysis involved four cases -- ships equipped with Escher-Wyss or PSI propellers, each operating with a trailing (rotating) or locked propeller shaft. Again, these data were added to the propeller diagrams (Figures 6-10 to 6-13) for ease of analysis and are shown in Figures 6-14 through 6-17.

Comparing the propeller diagrams for one- and two-engine operation, it was observed that the horsepower required to produce a given ship speed was at a minimum in the mid-pitch ratio range (1.0 - 1.2) for single-engine operation and in the two or three highest pitch settings under normal two-engine operation. This would be expected since conversion to single-engine operation essentially doubles the thrust from one propeller, requiring a reduction in pitch and an increase in shaft speed to maintain ship speed. Since fuel consumption and horsepower decrease when moving vertically down the propeller diagram, minimum fuel consumption at each ship speed is at the point of minimum horsepower. Therefore, preferred operation with two engines would be at the highest achievable pitch, and with one engine, at a slightly lower pitch.

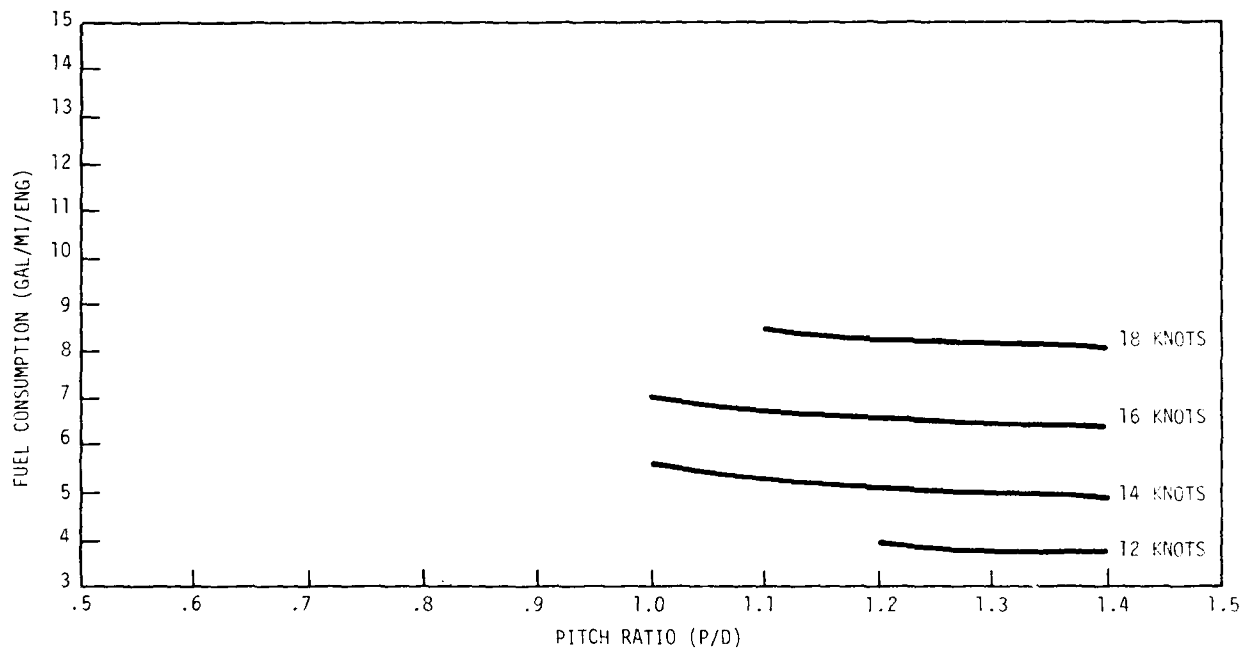


FIGURE 6-4. WHEC FUEL VOLUME FLOW RATE, ESCHER-WYSS ® PROPELLER

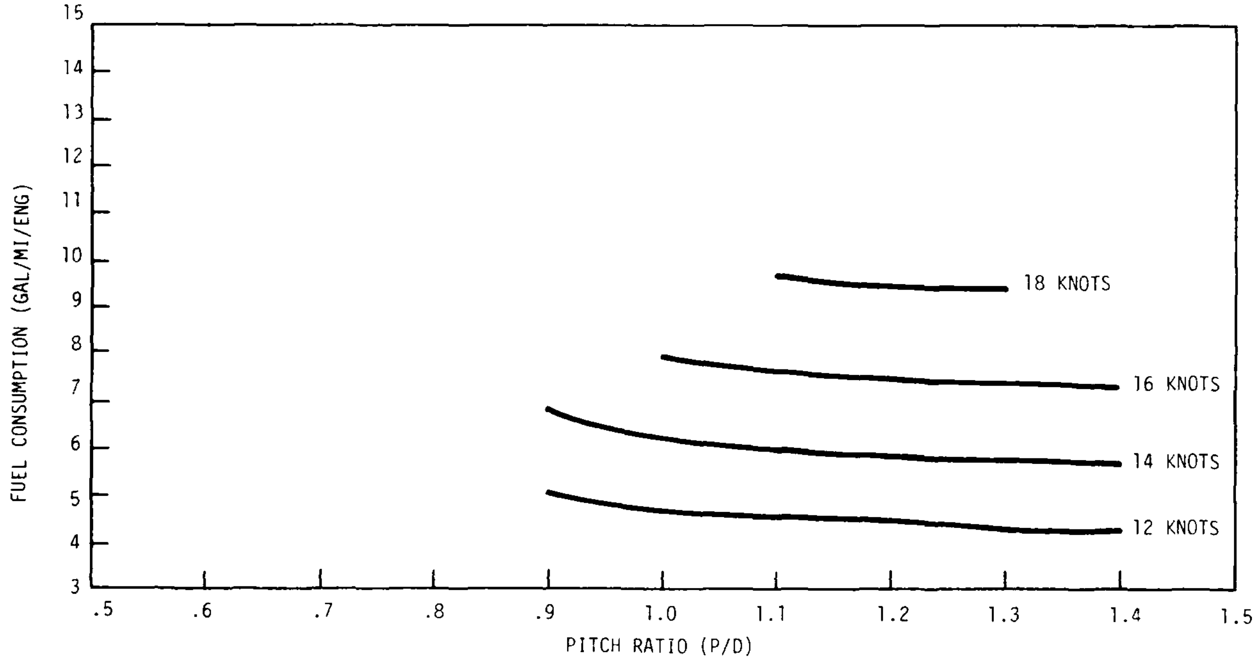


FIGURE 6-5. WHEC FUEL VOLUME FLOW RATE, PROPULSION SYSTEMS, INC.,® PROPELLER

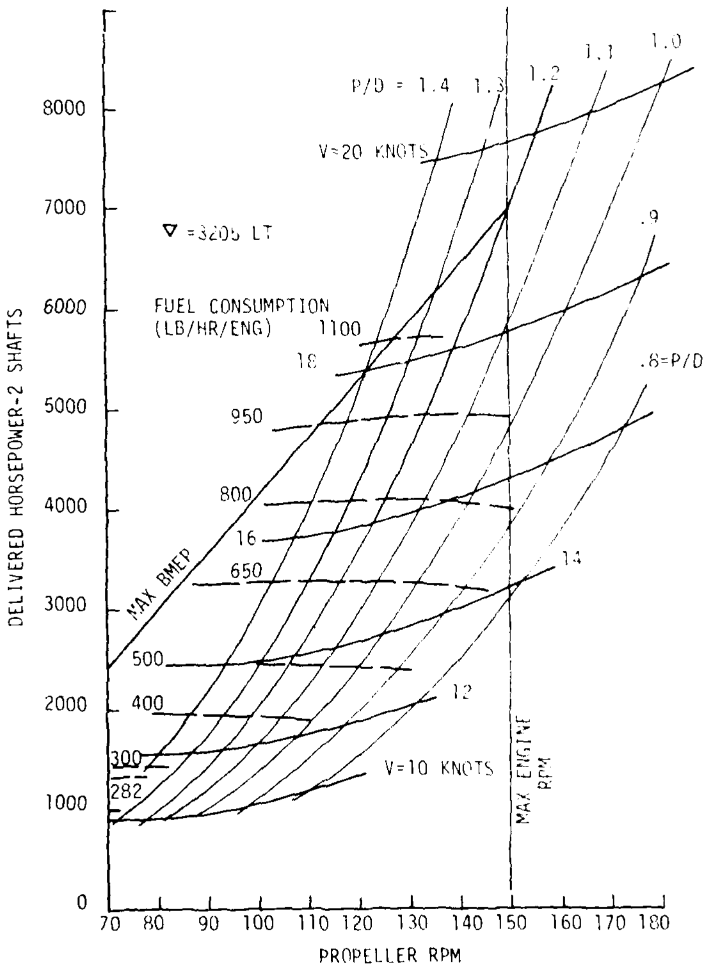


FIGURE 6-6. WHEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION, ESCHER-WYSS ® PROPELLER

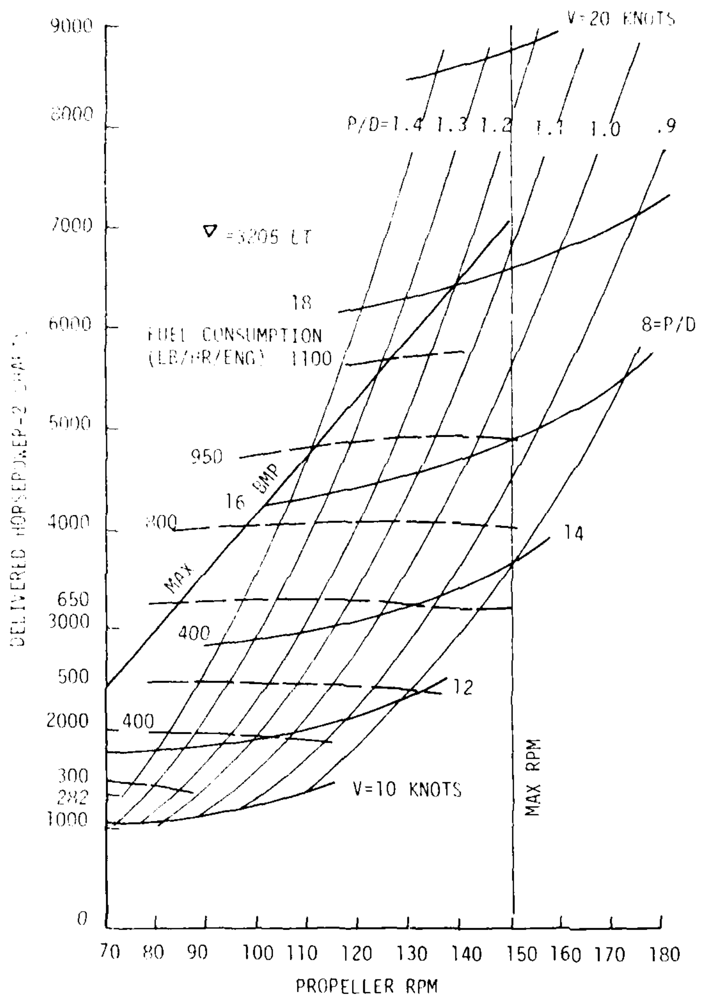


FIGURE 6-7. WHEC PROPELLER DIAGRAM WITH FUEL CONSUMPTION, PROPULSION SYSTEMS, INC. ® PROPELLER

TABLE 6-14a. CYCLE COMPOSITE FUEL CONSUMPTION -- WHEC ESCHER-WYSS ® PROPELLER

| Mode | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | lb/BHP-hr | Fuel Consumption | | Weighted Fuel Consumption | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | lb/hr/eng | gal/mi/eng | lb/hr/eng | gal/mi/eng. |
| Idle | 0 | 0 | 0 | 450 | 0 | - | - | - | - | - |
| 1/3 | 4 | .325 | .55 | 450 | 8 | 0.8 | 76.8 | 2.2 | 25 | 0.7 |
| 2/3 | 8 | .375 | 1.0 | 450 | 20 | .460 | 117 | 3.1 | 66.2 | 1.15 |
| Standard | 14 | .23 | 1.0 | 750 | 114 | .409 | 560 | 5.6 | 129 | 1.29 |
| Full | 17 | .07 | 1.0 | 900 | 203 | .388 | 945 | 7.75 | 66 | 0.54 |
| Flank | 17 | 0 | 1.0 | 900 | 203 | .388 | 945 | 7.75 | 0 | 0 |
| Totals | — | 1.0 | — | — | — | — | — | — | 286.2 | 3.68 |

TABLE 6-14b. OPTIMIZED FUEL CONSUMPTION -- WHEC ESCHER-WYSS PROPELLER

| Mode | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | lb/BHP-hr | Fuel Consumption | | Weighted Fuel Consumption | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | lb/hr/eng | gal/mi/eng | lb/hr/eng | gal/mi/eng |
| Idle | 0 | 0 | 0 | 450 | - | - | - | - | - | - |
| 1/3 | 4 | .325 | .55 | 450 | 8 | 0.8 | 76.4 | 2.7 | 25.[illegible] | 0.87 |
| 2/3 | 8 | .375 | 1.0 | 450 | 20 | .460 | 110.4 | 1.9 | 41.4 | 0.72 |
| Standard | 14 | .23 | 1.4 | 560 | 104 | .403 | 502.9 | 5.0 | 115.7 | 0.15 |
| Full | 17 | .07 | 1.4 | 690 | 184 | .392 | 865.5 | 7.1 | 60.6 | .495 |
| Flank | 19.5 | 0 | 1.22 | 900 | 300 | .387 | 1360.8 | 9.7 | 0 | 0 |
| Totals | — | 1.0 | — | — | — | — | — | — | 242.4 | 3.24 |

TABLE 6-15a. CYCLE COMPOSITE FUEL CONSUMPTION -- WHEC PROPULSION SYSTEMS INC. ® PROPELLER

| Mode | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | lb/BHP-hr | Fuel Consumption | | Weighted Fuel Consumption | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | lb/hr/eng | gal/mi/eng | lb/hr/eng | gal/mi/eng. |
| Idle | 0 | 0 | 0 | 450 | - | - | - | - | 0 | 0 |
| 1/3 | 5 | .325 | .53 | 450 | 14 | 0.8 | 134.4 | 3.8 | 43.7 | 1.23 |
| 2/3 | 9 | .375 | 1.0 | 450 | 32 | .445 | 171 | 2.6 | 64.1 | 0.99 |
| Standard | 14 | .23 | 1.0 | 750 | 129 | .403 | 624 | 6.2 | 143.5 | 1.43 |
| Full | 17 | .07 | 1.0 | 900 | 238 | .383 | 1094 | 8.9 | 76.6 | 0.63 |
| Flank | 17 | 0 | 1.0 | 900 | 128 | .383 | 1094 | 8.9 | 0 | 0 |
| Totals | — | 1.0 | — | — | — | — | — | — | 327.9 | 4.28 |

TABLE 6-15b. OPTIMIZED FUEL CONSUMPTION -- WHEC PROPULSION SYSTEMS INC. PROPELLER

| Mode | Ship Speed (Knots) | Modal Weight Factor | (P/D) Pitch Ratio | Engine RPM | BHP/cyl | lb/BHP-hr | Fuel Consumption | | Weighted Fuel Consumption | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | lb/hr/eng | gal/mi/eng | lb/hr/eng | gal/mi/eng |
| Idle | 0 | 0 | 0 | 450 | 0 | - | - | - | 0 | 0 |
| 1/3 | 5 | .325 | .55 | 450 | 14 | 0.8 | 134.4 | 3.8 | 43.7 | 1.23 |
| 2/3 | 9 | .375 | 1.0 | 450 | 32 | .445 | 170.9 | 2.6 | 64.1 | 0.99 |
| Standard | 14 | .23 | 1.4 | 565 | 120 | .399 | 574.6 | 5.7 | 132.1 | 1.31 |
| Full | 17 | .07 | 1.3 | 690 | 216 | .393 | 1018.6 | 8.9 | 71.3 | 0.58 |
| Flank | 18.0 | 0 | 1.15 | 900 | 300 | .378 | 1360.8 | 10.2 | 0 | - |
| Totals | — | 1.0 | — | — | — | — | — | — | 311.2 | 4.11 |

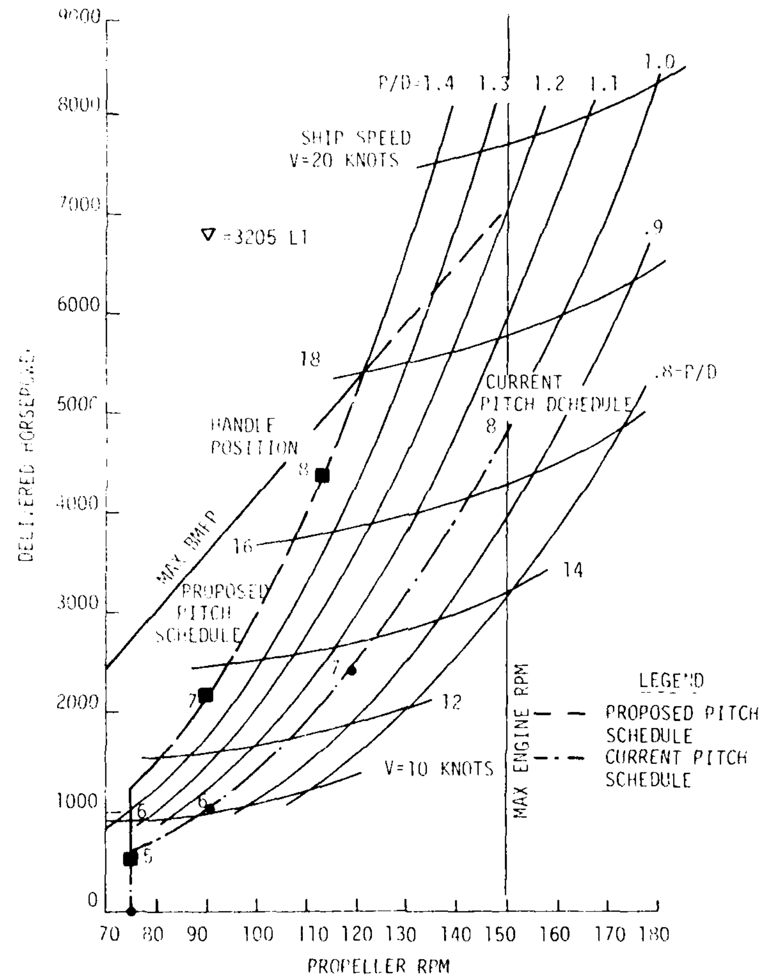


FIGURE 6-8. HYPOTHETICAL WHEC PITCH SCHEDULE, ESCHER-WYSS ® PROPELLER

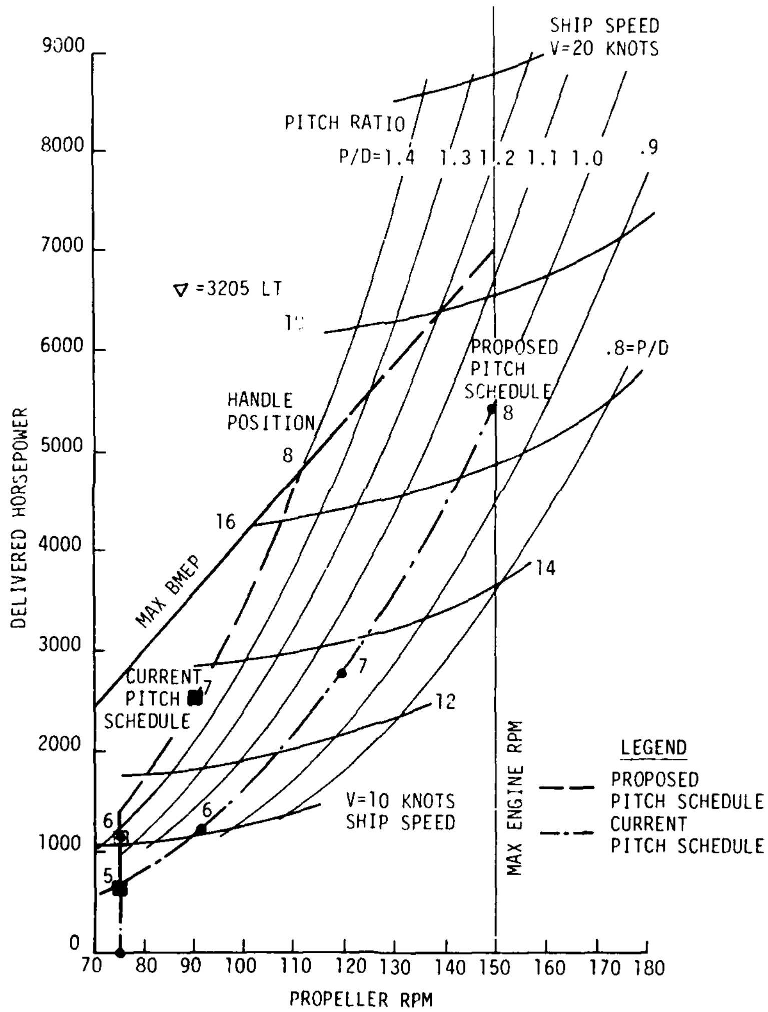


FIGURE 6-9. HYPOTHETICAL WHEC PITCH SCHEDULE, PROPULSION SYSTEMS, INC., ® PROPELLER

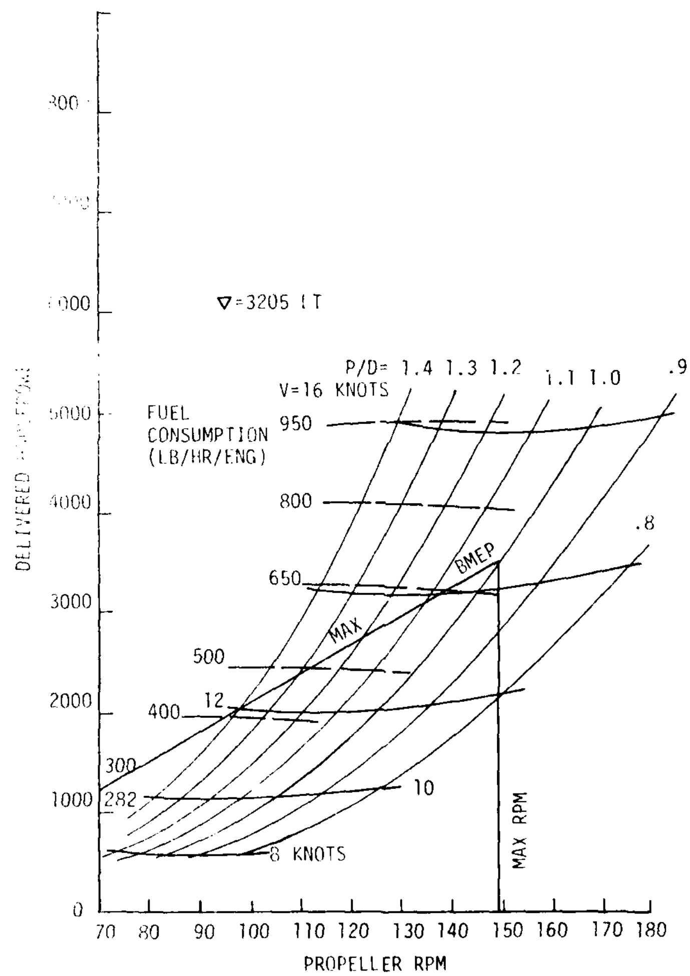


FIGURE 6-10. WHEC SINGLE ENGINE OPERATION, ESCHER-WYSS ® TRAIL SHAFT

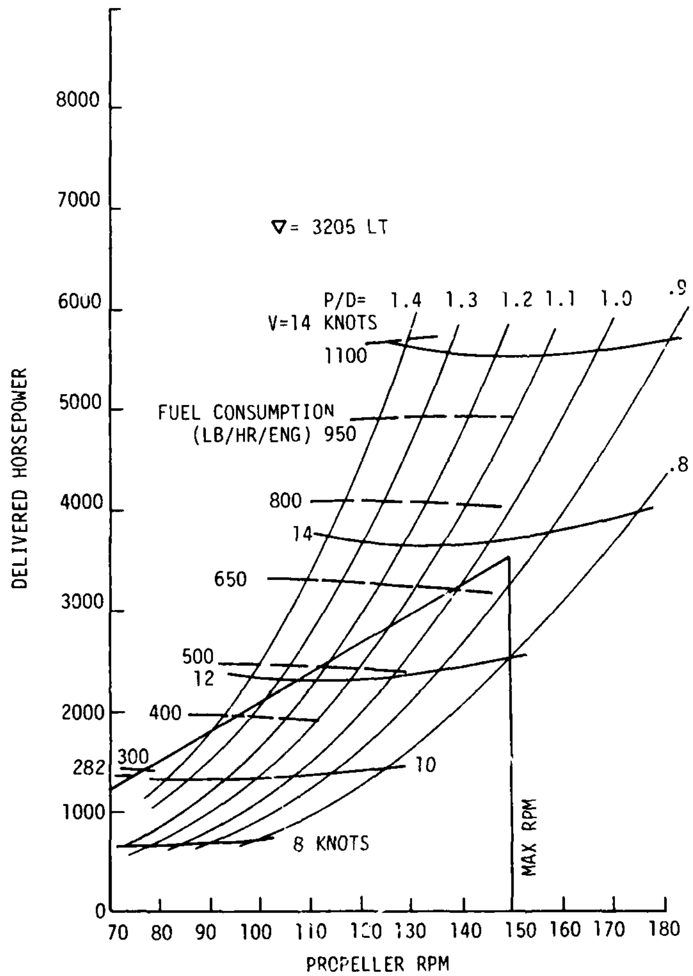


FIGURE 6-11. WHEC SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC.,® TRAIL SHAFT

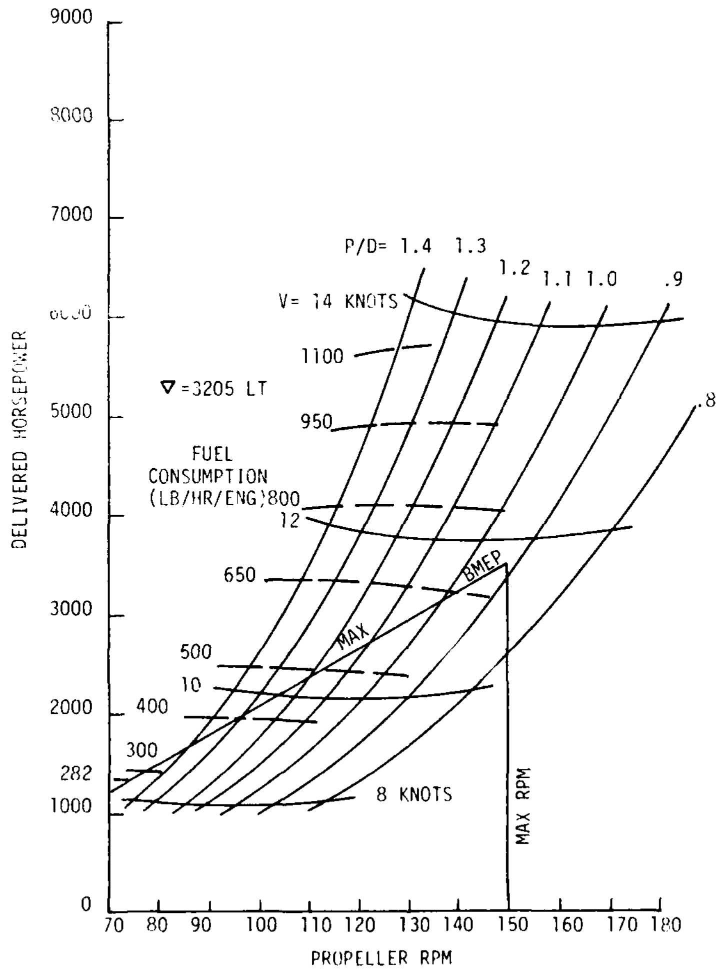


FIGURE 6-12. WHEC SINGLE ENGINE OPERATION, ESCHER-WYSS ® LOCKED SHAFT

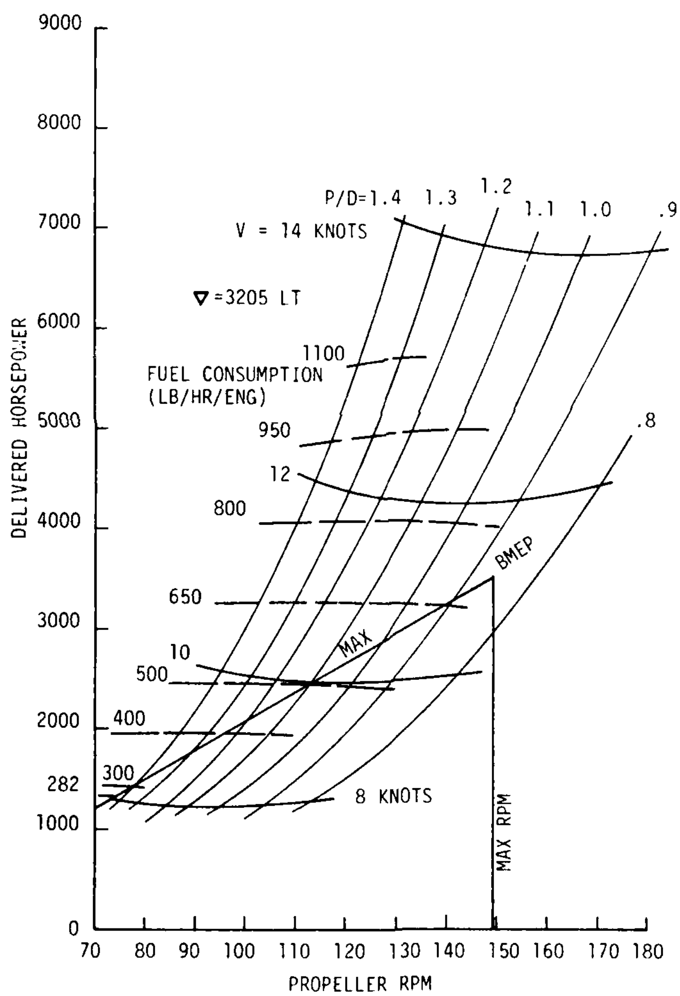


FIGURE 6-13. WHEC SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC.,® LOCKED SHAFT

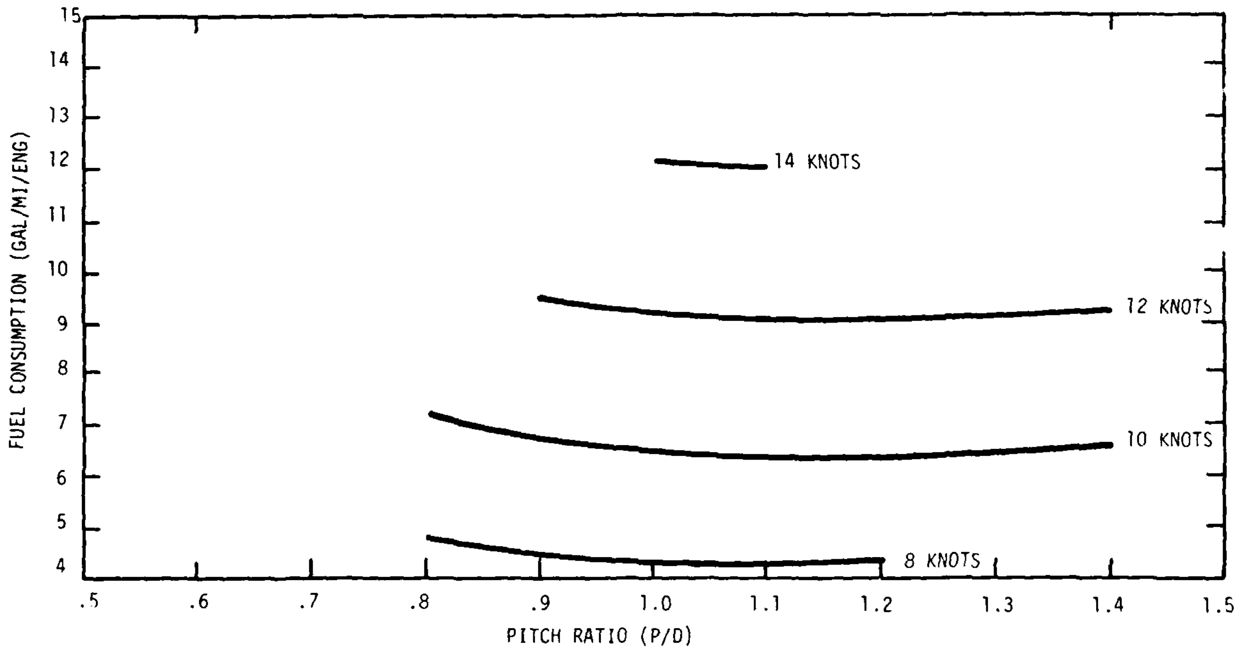


FIGURE 6-14. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, ESCHER-WYSS® PROPELLERS TRAIL SHAFT

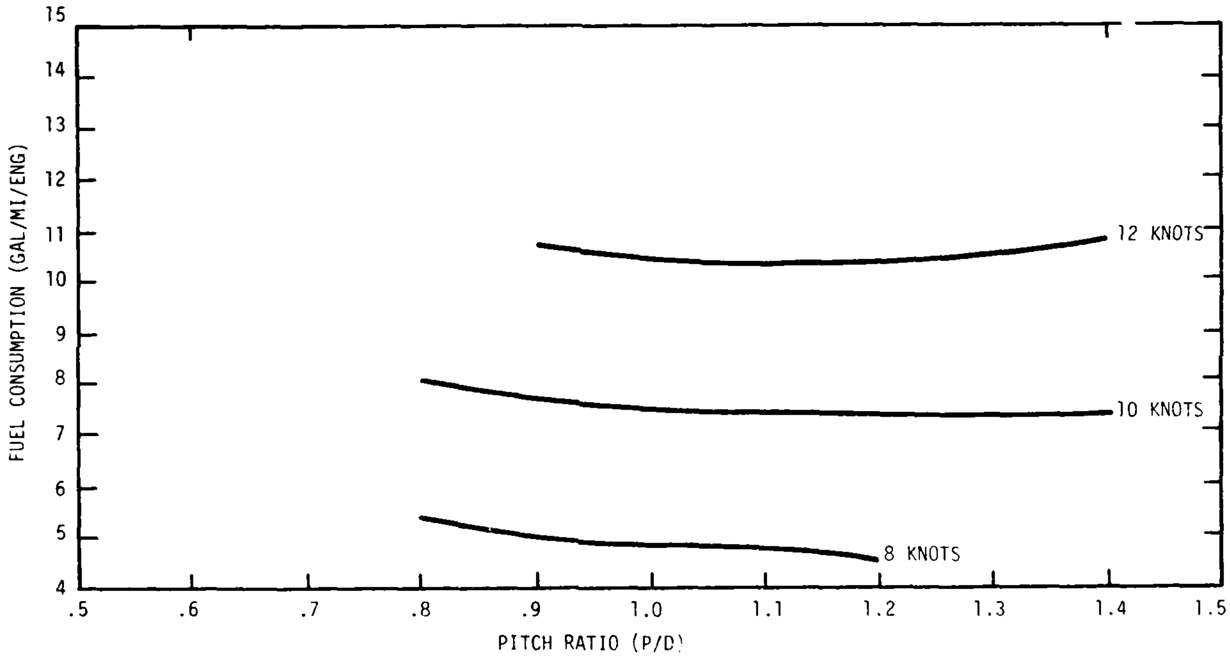


FIGURE 6-15. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ® PROPELLERS, TRAIL SHAFT

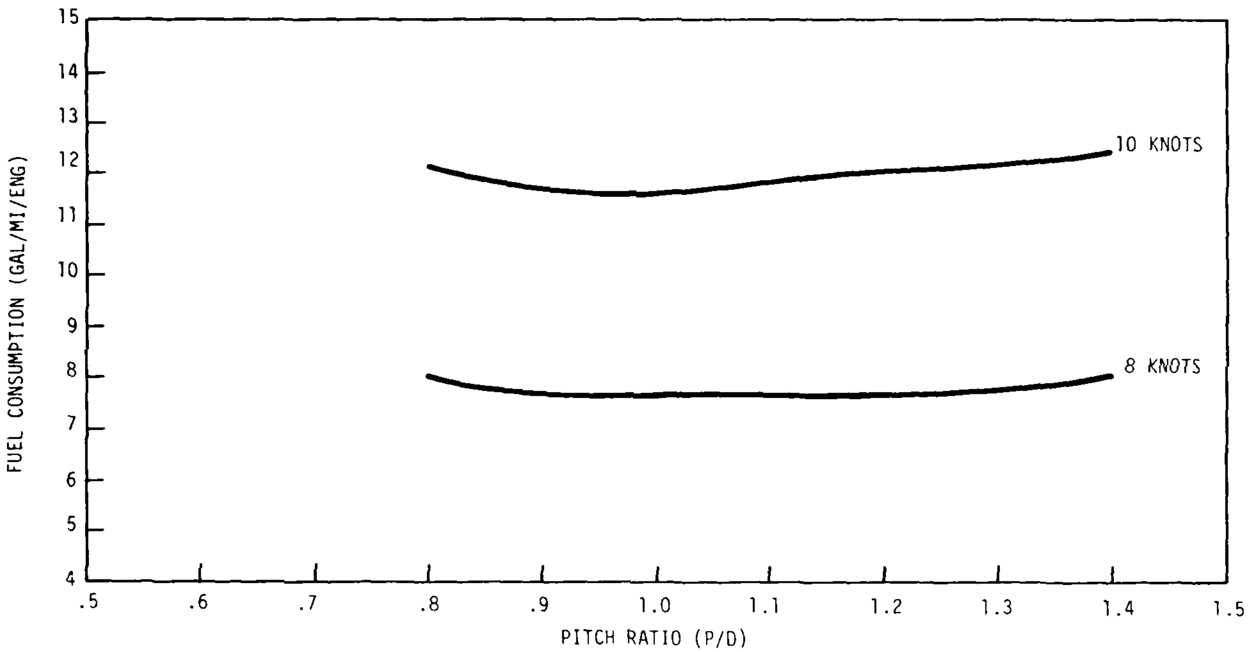


FIGURE 6-16. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, ESCHER-WYSS® PROPELLERS, LOCKED SHAFT

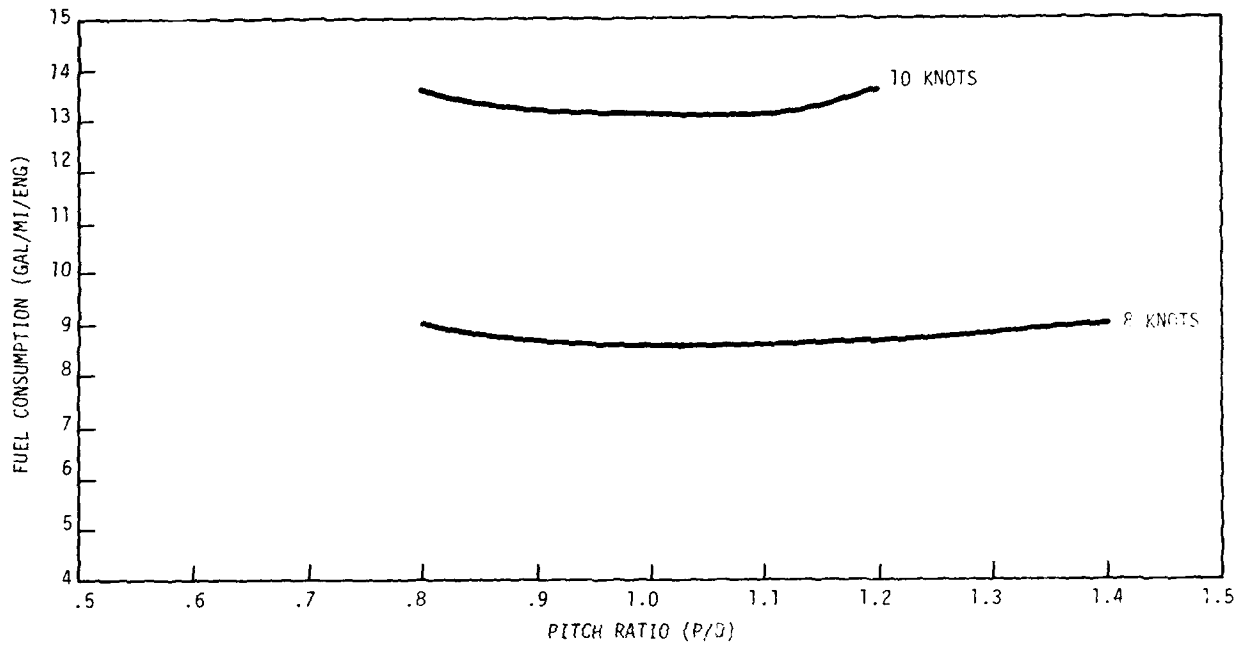


FIGURE 6-17. WHEC FUEL VOLUME FLOW RATE -- SINGLE ENGINE OPERATION, PROPULSION SYSTEMS, INC., ® PROPELLERS, LOCKED

Table 6-16 contains the optimum fuel consumption figures for various one- and two-engine configurations. In all cases, total fuel consumption for single-engine operation was greater than for two-engine operation at the same ship speed. However, data were not available for ship speeds below 10 knots. It is in this range that slow engine speed/low load conditions while operating on two engines could be transferred to higher speed/higher load combinations for a single engine, thus reducing brake specific fuel consumption and, possibly, reducing total fuel consumption. The data for this region could be obtained by expanding the low ship speed portion of the propeller diagram and the low speed/low load region of the engine performance map. This however, would require extensive additional analysis that was beyond the scope of this program.

The single-engine propeller diagrams verify Coast Guard observations that WHEC's can attain a speed of 10.5 knots at an engine speed of 660 RPM (109 propeller shaft RPM); standard practice is to use two engines above 10.5 knots.[7] The preferred type of operation would be with the free shaft rotating at maximum pitch since a locked shaft results in a large increase in drag and fuel consumption. (Therefore, provisions should be made to start the free propeller rotating in the event that it should stop.) The propeller diagrams and fuel consumption figures also reflect previous observations that the Escher-Wyss is the more efficient of the two propellers presently employed on the WHEC's.

TABLE 6-16. 378-FOOT SINGLE PROPELLER OPERATION

| Type of Operation | Ship Speed (Knots) | Escher-Wyss® Propellers Pitch Ratio (P/d) | Escher-Wyss® Shaft RPM | Escher-Wyss® Engine RPM | Escher-Wyss® Total Fuel Consumption (lb/hr) | Escher-Wyss® Total Fuel Consumption (gal/mi) | Propulsion Systems Inc.® Propellers Pitch Ratio (P/d) | PSI Shaft RPM | PSI Engine RPM | PSI Total Fuel Consumption (lb/hr) | PSI Total Fuel Consumption (gal/mi) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Present 2 propeller cond. | 8 | - | - | - | - | - | - | - | - | - | - |
| Optimum 2 propeller cond. | 8 | - | - | - | - | - | - | - | - | - | - |
| Single Prop - Trail Shaft | 8 | 1.0 | 73.5 | 443 | 249 | 4.3 | 1.2 | 73 | 440 | 280 | 4.5 |
| Single Prop - Locked Shaft | 8 | 1.0 | 95.5 | 576 | 442 | 7.7 | 1.1 | 99.5 | 540 | 493 | 8.6 |
| Present 2 propeller cond. | 10 | 1.0 | 89.5 | 540 | ~438 | ~6.2 | 1.0 | 89 | 537 | ~484 | ~6.8 |
| Optimum 2 propeller cond. | 10 | 1.3 | 72 | 434 | ~386 | ~5.4 | 1.3 | 72 | 434 | ~458 | ~6.4 |
| Single Prop - Trail Shaft | 10 | 1.2 | 92 | 555 | 459 | 6.4 | 1.2 | 92 | 555 | 528 | 7.4 |
| Single Prop - Locked Shaft | 10 | 1.0 | 120 | 724 | 830 | 11.6 | 1.1 | 112.5 | 679 | 943 | 13.1 |
| Present 2 propeller cond. | 12 | 1.0 | 107 | 646 | ~734 | 8.6 | 1.0 | 107 | 646 | 812 | 9.4 |
| Optimum 2 propeller cond. | 12 | 1.4 | 80.5 | 486 | 648 | 7.6 | 1.4 | 80.5 | 486 | 734 | 8.6 |
| Single Prop - Trail Shaft | 12 | 1.2 | 110.5 | 667 | 785 | 9.1 | 1.1 | 117.5 | 709 | 889 | 10.3 |
| Single Prop - Locked Shaft | 12 | - | - | - | - | - | - | - | - | - | - |
| Present 2 propeller cond. | 14 | 1.0 | 124 | 748 | 1120 | 11.2 | 1.0 | 124 | 748 | 1248 | 24.8 |
| Optimum 2 propeller cond. | 14 | 1.4 | 94 | 567 | 992 | 9.8 | 1.4 | 93.5 | 564 | 1138 | 11.4 |
| Single Prop - Trail Shaft | 14 | 1.1 | 136 | 821 | 1209 | 12.0 | - | - | - | - | - |
| Single Prop - Locked Shaft | 14 | - | - | - | - | - | - | - | - | - | - |
| Present 2 propeller cond. | 16 | 1.0 | 142 | 857 | 1616 | 14.0 | 1.0 | 142 | 857 | [illegible] | 13.8 |
| Optimum 2 propeller cond. | 16 | 1.4 | 107 | 646 | 1464 | 12.8 | 1.4 | 107 | 646 | 1688 | 14.6 |
| Single Prop - Trail Shaft | 16 | - | - | - | - | - | - | - | - | - | - |
| Single Prop - Locked Shaft | 16 | - | - | - | - | - | - | - | - | - | - |

Note: ~ indicates that the value of BSFC was extrapolated from the engine performance map.

# APPENDIX A

# WHEC PROPELLER DIAGRAM CORRECTIONS

PROPELLER DIAGRAMS FOR THE US COAST GUARD

378-FOOT HIGH-ENDURANCE CUTTER

for

Southwest Research Institute
San Antonio TX

by

W. S. Vorus

M. G. Parsons

Department of Naval Architecture and Marine Engineering
The University of Michigan
Ann Arbor MI

December 1978

The propeller diagrams requested by your purchase order no. 120337 are the attached Figures 1 and 2.

Figure 1 is for the ships equipped with the Escher-Wyss propellers, and Figure 2 is for the ships equipped with the Propulsion Systems, Inc. propellers, as indicated thereon. The figures reflect a ship full load displacement of 3025 LT, which is some 10% in excess of the displacement for which the two propellers were reportedly designed. The figures give delivered horsepower for diesel operation versus propeller RPM for values of propeller pitch ratio and ship speed. The delivered power, being the power at the propeller, should be around 97% of the power output at the reduction gear (SHP).

The procedure followed in constructing Figures 1 and 2 consisted of 3 parts:

1) Correction of the original EHP curve to allow for the overweight condition of the vessels.

2) Construction of the diagram for the Escher Wyss propellers.

3) Construction of the diagram for the PSI propellers.

Each of these parts is described in the following.

EHP CURVE

The original EHP test (TMB file 9021, dated June 1963) was conducted at an equivalent ship displacement of 2716 tons, corresponding to a draft of 13.5 ft with zero trim.

The actual full load condition of the ships is reported to correspond to a displacement of 3025 tons with a draft at the center of flotation of 14.4 ft. The curves of form for the ships then imply a 6.3% increase in wetted-surface over the original design condition of 2716 tons.

Using the ITTC-1957 friction line with $\Delta C_f = .0004$, the viscous component of the resistance was increased over the speed range in proportion to the increase in wetted-surface; the residuary resistance component was left unchanged.

The resulting EHP curve is included herein on Figure 3a. Figure 3a shows both the original and the corrected trial condition EHP curves; the original EHP is increased on the order of 3% by the vessel overweight.

ESCHER WYSS ® PROPELLER DIAGRAM

The EW diagram, Figure 1, represents, in essence, a correction and expansion of the low speed (diesel) region of the existing diagram (USCG Dwg. 719WPG-4400-118). The following steps were taken:

1) The existing diagram was very simply used to back-out the open-water characteristics ($K_t$, $K_q$ versus J) of the EW propeller in the speed range of interest.

2) The corrected EHP curve was used along with the $K_t$ - J curve from 1) to determine the new RPM/speed relationship.

3) The delivered power was calculated for the equilibrium RPM determined in 2) using the $K_q$ - J curve from 1).

PSI PROPELLER DIAGRAM

For this propeller the only available information considered to be reliable was the open-water curves at the design pitch ratio of 1.25 (PSI drawing no. 16055-B). A propeller diagram similar to that of the EW propeller was available, but obviously erroneous. The available PSI diagrams imply a substantially higher propeller open-water efficiency at the design pitch ratio than PSI actually achieved. The open-water curve at the design P/D (dwg. no. 16055-B) shows an efficiency at the design condition of about 64%. This is quite low for propellers of these general characteristics; the

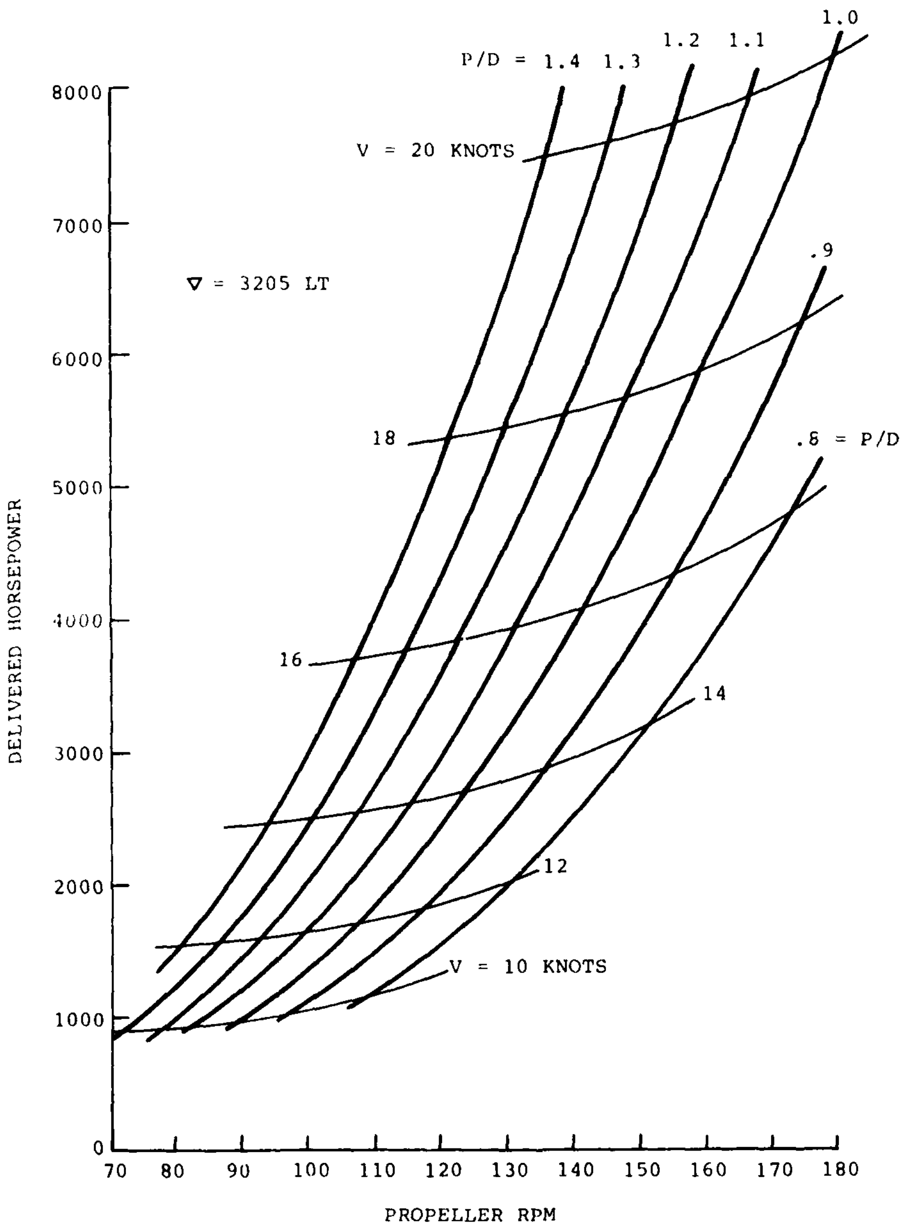


FIGURE A-1. USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS

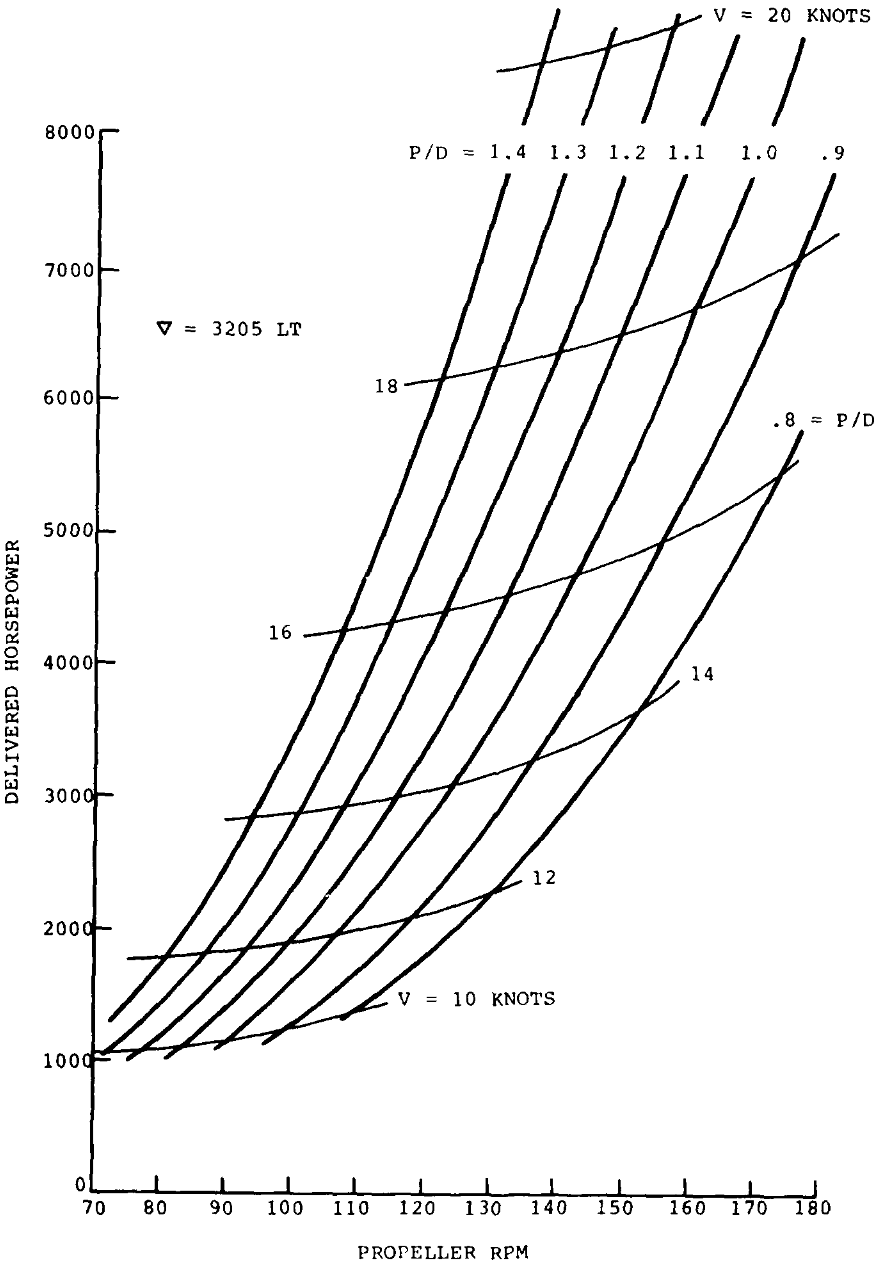


FIGURE A-2. USCG 378-FOOT HEC PROPULSION SYSTEMS, INC., ® PROPELLERS

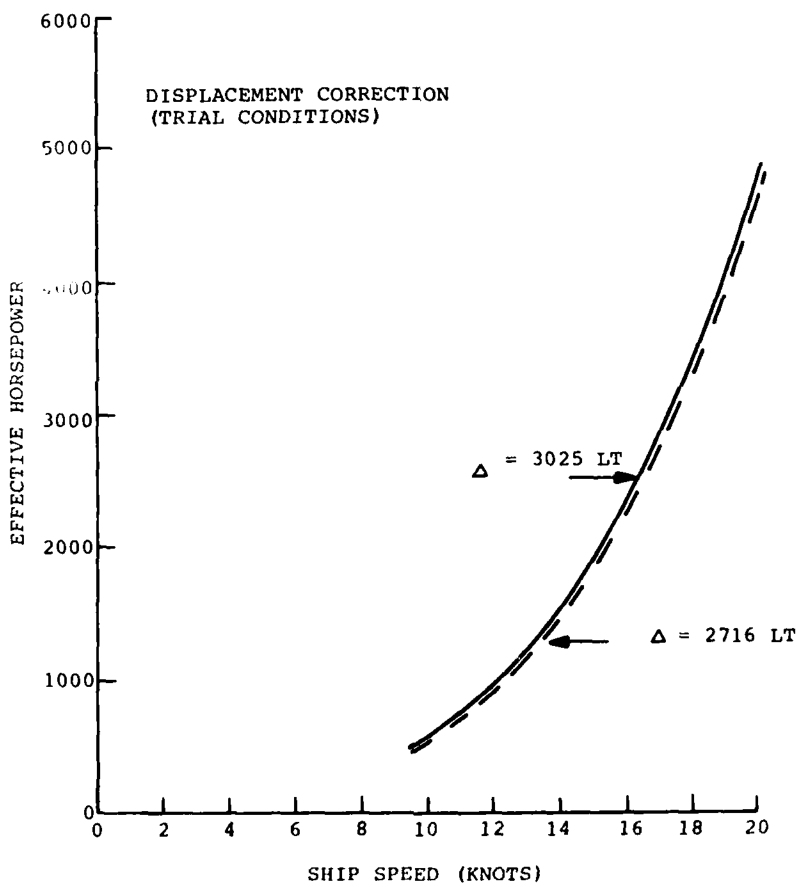


FIGURE A-3a. EHP VS. SPEED USCG 378-FOOT HEC

equivalent NSMB B4 series propeller has an open-water efficiency of 74%. A conjecture is that the diagrams might have been prepared with preliminary data based on a typically higher propeller efficiency and never corrected. The SHP curve from TMB file 9021, for example, implies a propeller efficiency in excess of 70%.

At any rate, the existing PSI diagram was deemed useless for the objectives of this work. The following steps were taken to produce Figure 2:

1) The $K_t$ - J curve for the PSI propeller at the design P/D matches almost exactly that constructed, as described above, for the EW propeller at the same P/D. This would not be unexpected since the design RPM-speed-pitch characteristics of the 2 propellers are virtually identical. The $K_t$ - J curves for the PSI propeller were therefore assumed to be the same as the $K_t$ - J curves for the EW propeller at all pitch ratios of interest.

2) The efficiency difference between the PSI and EW propellers was known at the design P/D only (the maximum efficiency of the EW propeller at P/D = 1.25 was calculated to be 73% from the $K_t$, $K_q$, J curves constructed as described above). This maximum efficiency difference, percentage-wise, was assumed to be the same at all P/D. This established one point on the family of $K_q$ - J curves for the PSI propeller. The values of J at $K_q = 0$ was then assumed to be the same for both propellers at corresponding pitch ratios. The two points then established the essentially linear $K_q$ - J characteristics for the PSI propeller in the speed range of interest.

3) With the open-water characteristics of the PSI propeller in hand, the additional steps followed in constructing Figure 2 were identically the same as steps 2) and 3) for the EW propeller and Figure 1 as described above. Actually, with the same $K_t$ - J curves the speed/RPM relationships from step 2) of the EW procedure apply for the PSI propeller; only step 3) of the EW procedure had actually to be executed to complete the data needed for the construction of Figure 2.

With regard to the accuracy of this work, it is expected that Figure 1 is as accurate as its input, and Figure 2 is within 2% of the accuracy of its input.

There appears to be no good reason to question the accuracy of the input data used, with one reservation: this involves the last paragraph on page 3 of the SWR Progress Report No. 9 to the USCG. This paragraph states the observation that the ships equipped with the Escher Wyss propeller turn slow; pitch must be reduced to P/D ≈ 1.1 to attain the design RMP at full power. To the contrary, Figure 1 shows that the EW propeller should achieve the design full power RPM at near the design P/D. It is the PSI propeller that this work would predict to turn slow at the design P/D. Figure 2, in fact, implies a pitch ratio of very near 1.1 at the full power and RPM. This is, of course, due to the low efficiency of the PSI propeller relative to that of the EW propeller, whose efficiency is not unusually high.

Again, a conjecture is that the statement on page 3 of the progress report has the EW and PSI propellers confused. Confirmation of this conjecture should remove all reservations regarding the reliability of Figures 1 and 2.

Author's Note: The conjecture in the final paragraph was found to be true, verifying the contents of this report.

PROPELLER DIAGRAMS FOR THE US COAST GUARD
378-FOOT HIGH ENDURANCE CUTTER; LOCKED AND
TRAIL SHAFT CONDITIONS

for

Southwest Research Institute
San Antonio TX

by

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M. G. Parsons

Department of Naval Architecture and Marine Engineering
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September 1979

The work requested by your purchase order no. 146811 has been completed and is reported herein. This work is supplementary to that previously reported in reference 1. In reference 1 propeller diagrams were developed for the U.S. Coast Guard 378-foot High Endurance Cutters for diesel operation. As two different propellers are installed on different ships within the class, two propeller diagrams were delivered with reference 1: one for ships equipped with Escher Wyss propellers, and one for the ships equipped with Propulsion Systems, Inc. propellers.

The subject purchase order subsequently requested that additional propeller diagrams be developed for the same ships operating with one of the two main engines secured. However, two modes of operation on one engine are apparently possible for the subject ships: 1) a locked shaft mode where the inoperable propeller is restrained from rotating by a shaft locking device, and 2) a trail shaft mode where the inoperable system is allowed to rotate in response to hydrodynamic torque developed by the trailing propeller. In order to cover the two single engine operating modes on all ships, it was therefore necessary to develop four new propeller diagrams; these diagrams are Figures 3 through 6 of this report. Figures 3 and 5 are the trail and locked shaft diagrams for the Escher Wyss propellers and Figures 4 and 6 are the corresponding diagrams for the PSI propellers.

The effect of the trailing or locked propeller is to increase the apparent resistance of the hull as seen by the driving propeller. Therefore, in constructing Figures 3 through 6, the EPH data of reference 1 was first augmented by appropriate amounts to allow for the locked or trailing propeller. The propeller open-water curves developed in connection with reference 1 were then used as described therein, along with the augmented EHP data, to construct the new Figures 3 through 6.

The resistance augmentation of the inoperable propeller at any speed was taken as the negative propeller thrust developed at that speed. The CP propeller data presented in reference 2 was used for this purpose. In the locked shaft cases the thrust was taken as the zero RPM value corresponding to the ship speed of interest. For the trail shaft estimates an iteration was first performed in order to determine the RPM of the trailing propeller as a function of ship speed. This equilibrium RPM was estimated by balancing the propeller hydrodynamic torque against the friction torque developed in the rotating propulsion system. The system friction torque was taken as 14% of the steady ahead torque at any RPM on the basis of data contained in reference 3. The CP propeller data from reference 2, with a correction for efficiency differences, was used to estimate the propeller hydrodynamic torque. On determining the equilibrium RPM in the trailing condition at a selected speed, the negative thrust required was then extracted directly from reference 2.

The accuracy of the Figures 3b through 6 data is considered to be consistent with that presented on Figures 1, 2 and 3a of reference 1.

REFERENCES

1. "Propeller Diagrams for the US Coast Guard 378-Foot High Endurance Cutter," by W.S. Vorus and M.G. Parsons, dated December 1978.

2. Strom-Tejsen, J., and Porter, R.R., "Prediction of Controllable-Pitch Propeller Performance in Off-Design Conditions," Third Ship Control Symposium, Bath, UK, 1972.

3. "Marine Diesel Power Plant Performance Practices," SNAME T&R Bulletin #3-27, 1973.

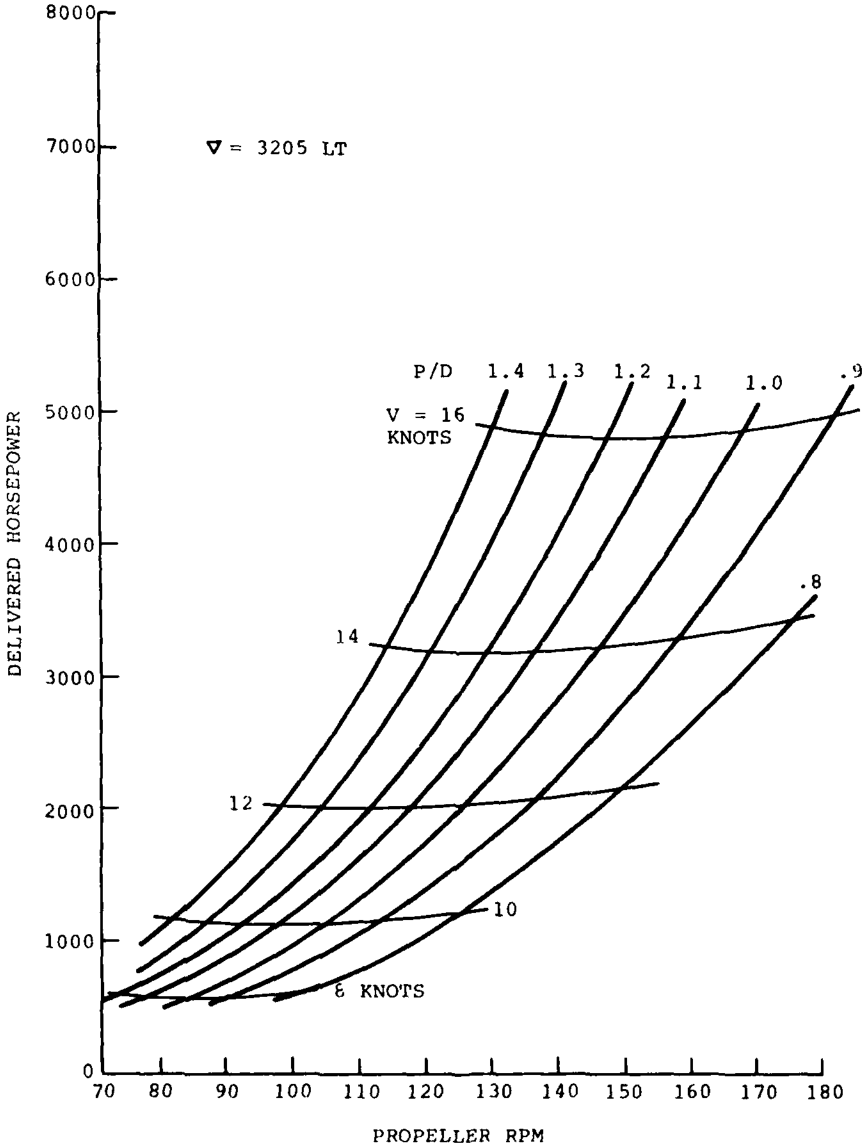


FIGURE A-3b. USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS TRAIL SHAFT

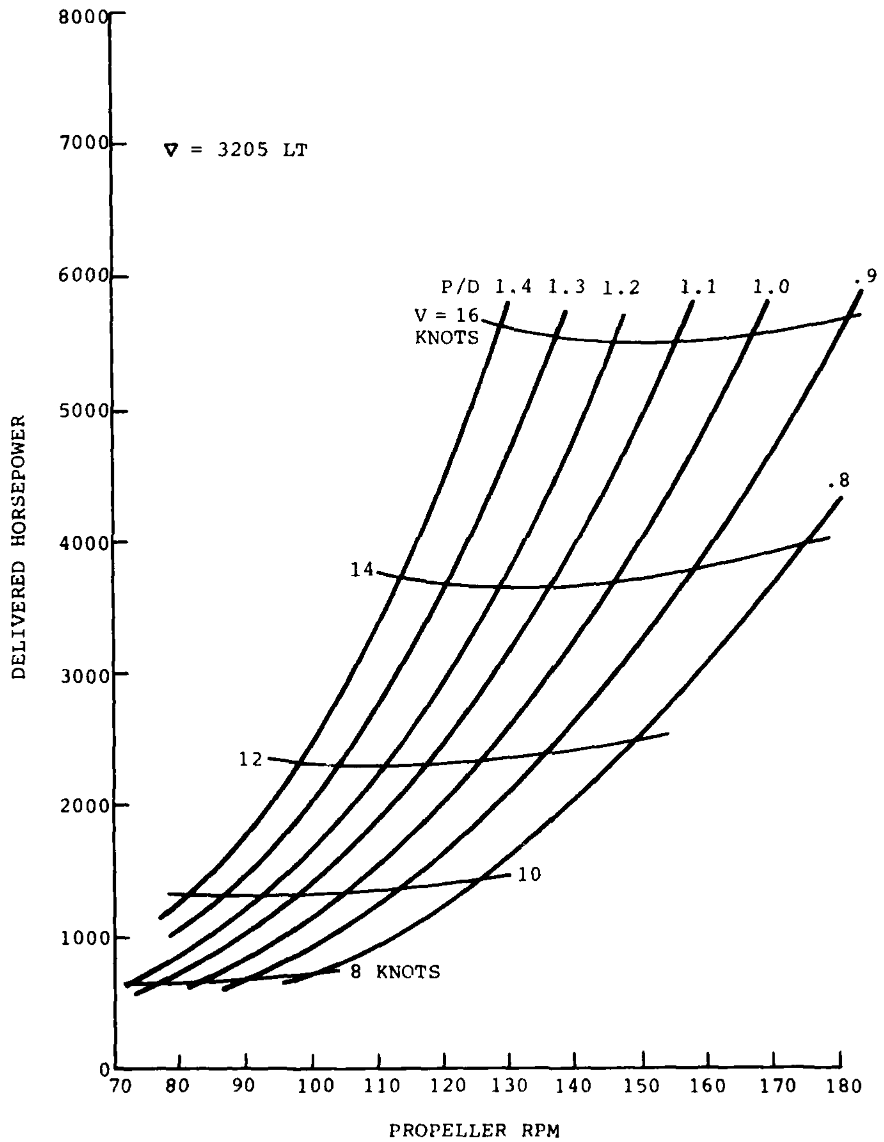


FIGURE A-4. USCG 378-FOOT HEC PROPULSION SYSTEMS, INC.,® PROPELLERS TRAIL SHAFT

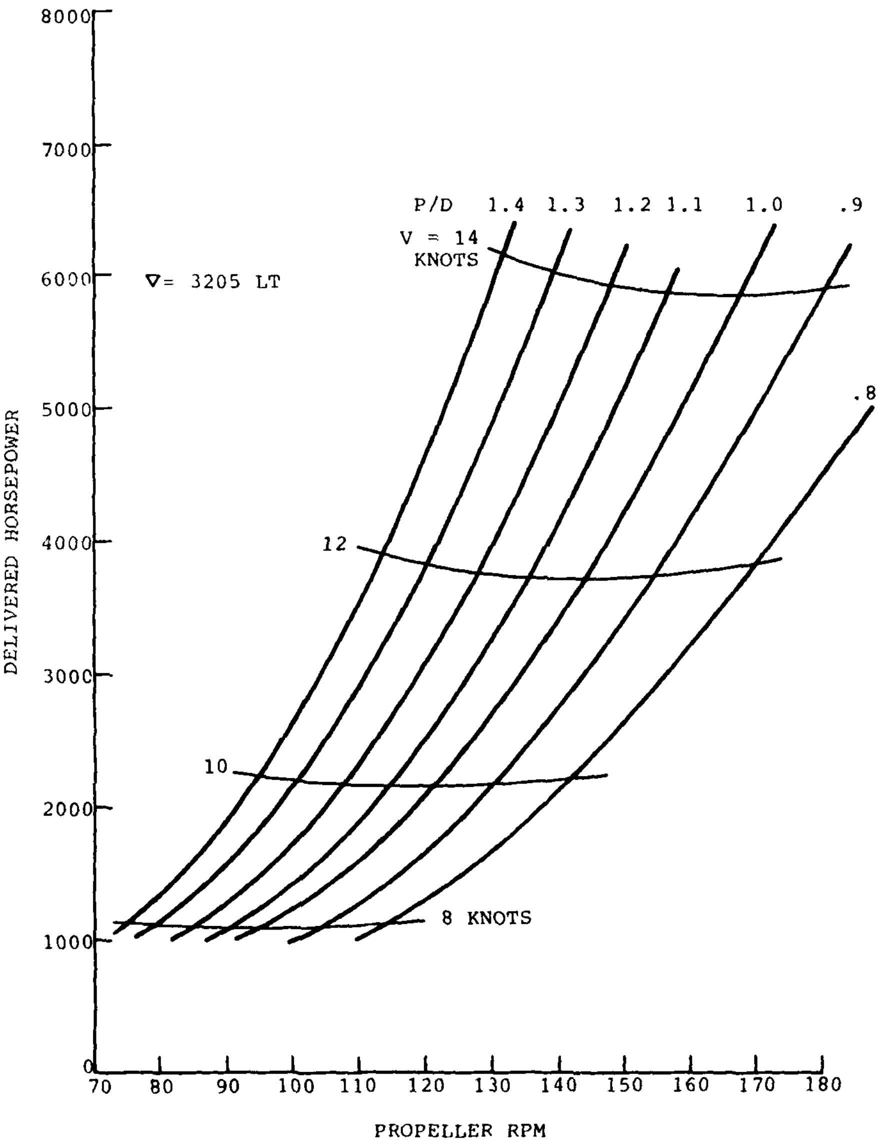


FIGURE A-5. USCG 378-FOOT HEC ESCHER-WYSS ® PROPELLERS LOCKED SHAFT

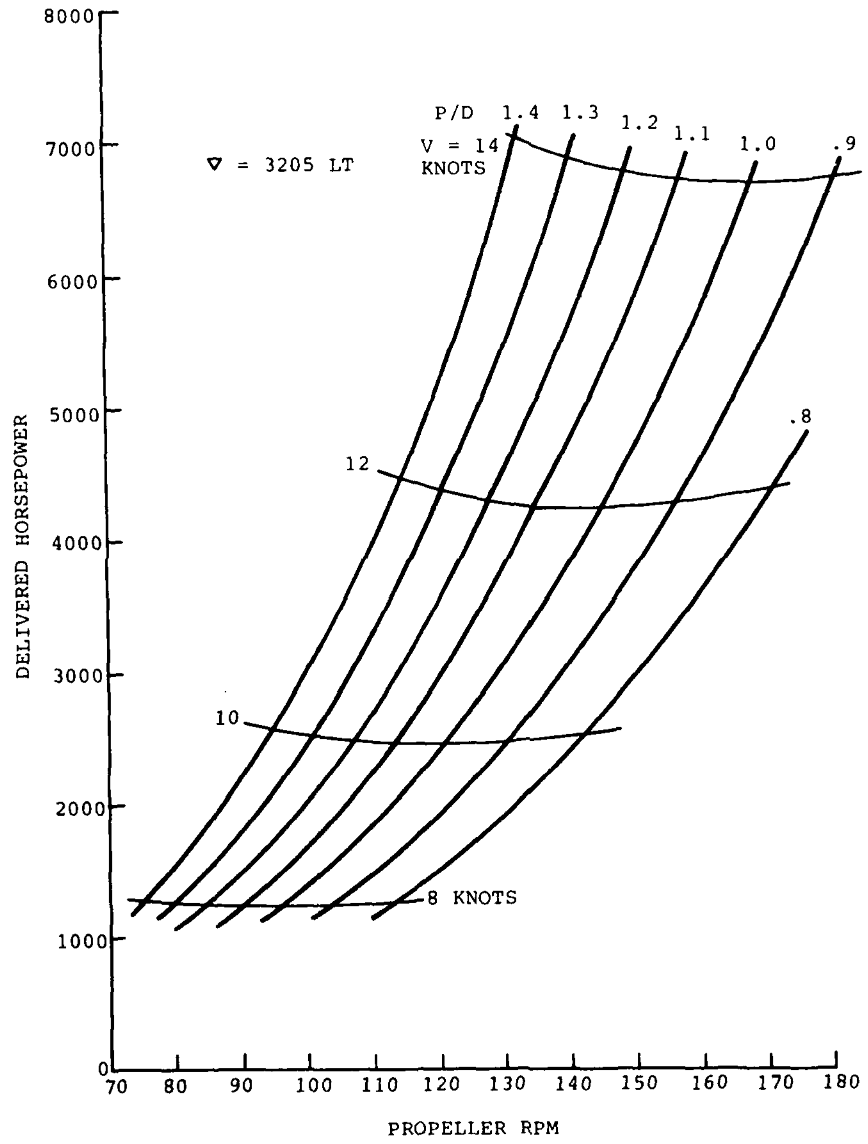


FIGURE A-6. USCG 378-FOOT HEC PROPULSION SYSTEMS, INC., ® PROPELLERS LOCKED SHAFT

APPENDIX B

FUEL CONSUMPTION CALCULATIONS FOR WHEC AND WMEC

378-FOOT WHEC MAIN DIESEL ENGINE FUEL CONSUMPTION DATA, PSI PROPELLER, NORMAL 2 PROPELLER OPERATION

| Ship Speed, Knots | SHP | SRPM | ERPM | BHP/Cyl. | BSFC | Fuel Consumption | | % Incr. from Lowest value |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $Lb_m$/hr/eng. | gal/mi/eng. | |
| P.R.= 1.4 | | | | | | | | |
| 10 | - | - | - | - | - | - | - | - |
| 12 | 1775 | 80.5 | 486 | 74.0 | .412 | 367 | 4.3 | 0 |
| 14 | 2850 | 93.5 | 564 | 118.8 | .399 | 569 | 5.7 | 0 |
| 16 | 4275 | 107 | 646 | 178 | .395 | 844 | 7.3 | 0 |
| 18 | 6200 | 121.5 | 733 | 258 | - | - | - | - |
| 20 | 8550 | 136 | 821 | 356 | - | - | - | - |
| P.R.= 1.3 | | | | | | | | |
| 10 | 1050 | 72 | 434 | 44 | >.420 | >.222 | >3.1 | 0 |
| 12 | 1800 | 86 | 519 | 75 | .414 | 373 | 4.3 | 0 |
| 14 | 2900 | 101 | 609 | 121 | .399 | 579 | 5.8 | 1.7 |
| 16 | 4350 | 114.5 | 691 | 181 | .392 | 851 | 7.4 | 1.4 |
| 18 | 6275 | 129.5 | 781 | 261 | .386 | 1209 | 9.4 | 0 |
| 20 | 8700 | 145.5 | 878 | 363 | - | - | - | - |
| P.R.= 1.2 | | | | | | | | |
| 10 | 1075 | 77.5 | 468 | 45 | >.420 | >227 | >3.2 | |
| 12 | 1850 | 92.5 | 558 | 77 | .415 | 383 | 4.5 | 4.7 |
| 14 | 2950 | 107.5 | 649 | 123 | .400 | 590 | 5.9 | 3.4 |
| 16 | 4425 | 123 | 742 | 184 | .389 | 859 | 7.5 | 2.7 |
| 18 | 6375 | 139.5 | 842 | 266 | .381 | 1216 | 9.4 | 0 |
| 20 | 8875 | 155.5 | 938 | 370 | - | - | - | - |
| P.R.= 1.1 | | | | | | | | |
| 10 | 1100 | 82.5 | 498 | 46 | >.420 | >232 | >3.2 | |
| 12 | 1900 | 99.5 | 600 | 79 | .416 | 394 | 4.6 | 7.0 |
| 14 | 3000 | 115 | 694 | 125 | .401 | 602 | 6.0 | 5.3 |
| 16 | 4525 | 131 | 790 | 189 | .389 | 882 | 7.7 | 5.5 |
| 18 | 6525 | 148.5 | 896 | 271 | .380 | 1236 | 9.6 | 2 1 |
| 20 | - | - | - | - | - | - | - | - |
| P.R.= 1.0 | | | | | | | | |
| 10 | 1150 | 89 | 537 | 48 | >.420 | > 242 | > 3.4 | |
| 12 | 1950 | 107 | 646 | 81 | .418 | 406 | 4.7 | 9.3 |
| 14 | 3100 | 124 | 748 | 129 | .403 | 624 | 6.2 | 8.8 |
| 16 | 4700 | 142 | 857 | 196 | .388 | 913 | 7.9 | 8.2 |
| 18 | 6775 | 160.5 | 968 | 282 | - | - | - | - |
| 20 | - | - | - | - | - | - | - | - |
| P.R.= 0.9 | | | | | | | | |
| 10 | 1200 | 97.5 | 588 | 50 | >.420 | >252 | >3.5 | |
| 12 | 2075 | 117 | 706 | 86 | >.420 | 433 | 5.0 | 16.3 |
| 14 | 3300 | 136 | 821 | 138 | .404 | 669 | 6.7 | 17.5 |
| 16 | 4950 | 155.5 | 938 | 206 | - | - | - | - |
| 18 | 7150 | 175 | 1056 | 298 | - | - | - | - |
| 20 | - | - | - | - | - | - | - | - |
| P.R.= 0.8 | 1350 | 109 | 658 | 56 | >.420 | >282 | >3.9 | |
| 12 | 2300 | 130 | 784 | 96 | >.420 | >484 | >5.6 | |
| 14 | 3675 | 151.5 | 914 | 153 | - | - | - | - |
| 16 | 5525 | 173.5 | 1047 | 230 | - | - | - | - |
| 18 | - | - | - | - | - | - | - | - |
| 20 | - | - | - | - | - | - | - | - |

**Note:** > indicates values which were approximated.

WHEC CONSTANT FUEL CONSUMPTION DATA - MAIN DIESEL ENGINE

| Fuel Cons. lb/hr/eng. | BSFC lb/Bhp-hr | Bhp/Cyl. | ERPM | SRPM | Shaft Hp. (2 shafts) |
|---|---|---|---|---|---|
| 282 | .420 | 56 | 400 | 66 | 1344 |
| 282 | .420 | 56 | 440 | 73 | 1344 |
| 300 | .420 | 59.5 | 480 | 79.5 | 1429 |
| 300 | .420 | 59.5 | 375 | 62.1 | 1429 |
| 400 | .42 | 79.4 | 650 | 108 | 1906 |
| 400 | .41 | 81.3 | 440 | 73 | 1951 |
| 400 | .41 | 81.3 | 530 | 88 | 1951 |
| 500 | .42 | 99.2 | 770 | 128 | 2381 |
| 500 | .41 | 101.6 | 405 | 67 | 2439 |
| 500 | .41 | 101.6 | 685 | 114 | 2439 |
| 650 | .41 | 137.1 | 435 | 72 | 3171 |
| 650 | .41 | 137.1 | 865 | 143 | 3171 |
| 650 | .40 | 135.4 | 500 | 83 | 3250 |
| 650 | .40 | 135.4 | 740 | 123 | 3250 |
| 650 | .399 | 135.8 | 585 | 97 | 3259 |
| 650 | .399 | 135.8 | 640 | 106 | 3259 |
| 800 | .399 | 167.1 | 895 | 148 | 4010 |
| 800 | .399 | 167.1 | 590 | 98 | 4010 |
| 800 | .400 | 167 | 543 | 88 | 4000 |
| 800 | .395 | 168.8 | 650 | 108 | 4051 |
| 800 | .395 | 168.8 | 860 | 143 | 4051 |
| 950 | .399 | 198.4 | 620 | 103 | 4762 |
| 950 | .395 | 200.4 | 660 | 109 | 4810 |
| 950 | .390 | 203 | 710 | 118 | 4872 |
| 950 | .387 | 204.6 | 770 | 128 | 4910 |
| 950 | .387 | 204.6 | 875 | 145 | 4910 |
| 1100 | .390 | 235 | 735 | 122 | 5641 |
| 1100 | .387 | 237 | 760 | 126 | 5685 |
| 1100 | .385 | 238 | 800 | 133 | 5714 |

MAIN DIESEL ENGINE FUEL CONSUMPTION DATA--WMEC 210B

| Fuel Cons. lb/hr/eng. | bsfc lb/Bhp-hr. | Engine BHP/cyl. | ERPM | SRPM | Shaft Hp |
|---|---|---|---|---|---|
| 150 | .40 | 23.4 | 650 | 195 | 375 |
| 350 | .40 | 54.7 | 975 | 293 | 875 |
| | .365 | 59.9 | 455 | 137 | 959 |
| | .365 | 59.9 | 815 | 245 | 959 |
| 550 | .365 | 94.2 | 515 | 155 | 1507 |
| | .355 | 96.8 | 605 | 182 | 1549 |
| | .355 | 96.8 | 985 | 296 | 1549 |
| | .350 | 98.2 | 825 | 243 | 1571 |
| 750 | .355 | 132.0 | 655 | 197 | 2113 |
| | .350 | 133.9 | 712 | 214 | 2143 |
| | .348 | 134.7 | 755 | 227 | 2155 |
| | .345 | 135.9 | 880 | 264 | 2174 |
| 950 | .348 | 170.6 | 820 | 246 | 2730 |
| | .345 | 172.1 | 885 | 266 | 2754 |
| | .340 | 174.6 | 945 | 284 | 2794 |
| 1150 | .335 | 214.6 | 1030 | 309 | 3433 |

CONSTANT FUEL CONSUMPTION DATA - SINGLE MAIN DIESEL ENGINE

| Ship Speed Knots | SHP | SRPM | ERPM | Fuel Cons., $lb_m$/hr/eng. | % Increase from Lowest Value | Fuel Cons., gal/mi/eng. | % Increase from lowest value |
|---|---|---|---|---|---|---|---|
| **P.R. = 1.30** | | | | | | | |
| 12 | 358 | 157 | 523 | 141.4 | 0.6 | 1.6 | - |
| 13 | 477 | 171 | 570 | 183.6 | - | 2.0 | - |
| 14 | 650 | 187 | 623 | 240.5 | - | 2.4 | - |
| 15 | 840 | 204 | 680 | 305.8 | - | 2.8 | - |
| 16 | 1068 | 220 | 733 | 382.3 | - | 3.3 | - |
| 17 | 1410 | 239 | 797 | 497.7 | - | 4.1 | - |
| 18 | 2033 | 265 | 883 | 701.4 | - | 5.4 | - |
| 18.6 | 2260 | 272 | 907 | 775.2 | - | 5.8 | - |
| **P.R. = 1.20** | | | | | | | |
| 12 | 356 | 166 | 553 | 140.6 | - | 1.6 | - |
| 13 | 477 | 181 | 603 | 183.6 | - | 2.0 | - |
| 14 | 652 | 199 | 663 | 243.2 | 1.1 | 2.4 | - |
| 15 | 838 | 216 | 720 | 305.9 | - | 2.8 | - |
| 16 | 1068 | 232 | 773 | 384.5 | 0.6 | 3.3 | - |
| 17 | 1408 | 251 | 837 | 498.4 | 0.1 | 4.1 | - |
| 18 | 2035 | 277 | 923 | 702.1 | 0.1 | 5.4 | - |
| 18.5 | 2425 | 291 | 970 | 824.5 | 6.4 | 6.2 | 6.9 |
| **P.R. = 1.10** | | | | | | | |
| 12 | 360 | 177 | 590 | 142.2 | 1.1 | 1.6 | - |
| 13 | 483 | 193 | 643 | 186.9 | 1.8 | 2.0 | - |
| 14 | 660 | 213 | 710 | 249.5 | 3.7 | 2.5 | 4.2 |
| 15 | 840 | 231 | 770 | 309.1 | 1.1 | 2.9 | 3.6 |
| 16 | 1072 | 248 | 827 | 389.1 | 1.8 | 3.4 | 3.0 |
| 17 | 1413 | 269 | 897 | 501.6 | 0.8 | 4.1 | - |
| 18 | 2042 | 297 | 990 | 702.4 | 0.1 | 5.4 | - |
| 18.1 | 2120 | 300 | 1000 | 727.2 | 3.7 | 5.6 | 3.7 |
| **P.R. = 1.00** | | | | | | | |
| 12 | 370 | 191 | 637 | 148.0 | 5.3 | 1.7 | 6.2 |
| 13 | 492 | 207 | 690 | 195.3 | 6.4 | 2.1 | 5.0 |
| 14 | 670 | 228 | 760 | 256.6 | 6.7 | 2.5 | 4.2 |
| 15 | 850 | 246 | 820 | 318.8 | 4.2 | 3.0 | 7.1 |
| 16 | 1083 | 266 | 887 | 395.3 | 3.4 | 3.4 | 3.0 |
| 17 | 1430 | 290 | 967 | 511.9 | 2.8 | 4.2 | 2.4 |
| 17.2 | 1615 | 300 | 1000 | 571.7 | 14.9 | 4.6 | 12.2 |
| **P.R. = 0.90** | | | | | | | |
| 12 | 382 | 208 | 693 | 154.7 | 10.0 | 1.8 | 12.5 |
| 13 | 510 | 226 | 753 | 204.0 | 11.1 | 2.2 | 10.0 |
| 14 | 687 | 246 | 820 | 267.9 | 11.4 | 2.7 | 12.5 |
| 15 | 870 | 265 | 883 | 333.2 | 9.0 | 3.1 | 10.7 |
| 16 | 1110 | 286 | 953 | 412.9 | 8.0 | 3.6 | 9.1 |
| 16.5 | 1285 | 300 | 1000 | 471.6 | 23.4 | 4.0 | 21.2 |
| **P.R. = 0.80** | | | | | | | |
| 12 | 400 | 227 | 757 | 168.0 | 19.5 | 1.9 | 18.8 |
| 13 | 535 | 247 | 823 | 218.3 | 18.9 | 2.3 | 15.0 |
| 14 | 727 | 272 | 907 | 290.8 | 20.9 | 2.9 | 20.8 |
| 15 | 917 | 293 | 977 | 362.2 | 18.4 | 3.4 | 21.4 |
| 15.3 | 987 | 300 | 1000 | 386.9 | 26.5 | 3.5 | 25.0 |
| **P.R. = 0.70** | | | | | | | |
| 12 | 435 | 251 | 837 | 187.0 | 33.0 | 2.2 | 37.5 |
| 13 | 575 | 272 | 907 | 243.2 | 32.5 | 2.6 | 30.0 |
| 14 | 785 | 300 | 1000 | 327.3 | 36.1 | 3.2 | 33.3 |
| **P.R. = 0.60** | | | | | | | |
| 12 | 505 | 289 | 963 | 224.7 | 59.8 | 2.6 | 62.5 |
| 12.4 | 568 | 300 | 1000 | 249.9 | 77.7 | 2.8 | 75.0 |

378-FOOT WHEC MAIN DIESEL ENGINE FUEL CONSUMPTION DATA

| Ship Speed, Knots | SHP (2 Shafts) | SRPM | ERPM | Engine BHP/cyl | BSFC lb/Bhp-hr | Fuel Consumption | | % Incr. from Lowest Value |
|---|---|---|---|---|---|---|---|---|
| | | | | | | lb/hr/eng | gal/mi/eng | |
| P.R.= 1.40 | | | | | | | | |
| 10 | - | - | - | - | - | - | - | - |
| 12 | 1550 | 80.5 | 486 | 64.6 | .418 | 324 | 3.8 | 0 |
| 14 | 2460 | 94 | 567 | 102.5 | .403 | 496 | 4.9 | 0 |
| 16 | 3700 | 107 | 646 | 154 | .396 | 732 | 6.4 | 0 |
| 18 | 5375 | 121.5 | 733 | 224 | .389 | 1046 | 8.1 | 0 |
| 20 | 7475 | 135.5 | 818 | 312 | - | - | - | - |
| P.R.= 1.3 | | | | | | | | |
| 10 | 875 | 72 | 424 | 36.5 | >.420 | >184 | >2.6 | 0 |
| 12 | 1575 | 86.5 | 521 | 65.5 | .420 | 331 | 3.8 | 0 |
| 14 | 2500 | 100.5 | 606 | 104.2 | .405 | 506 | 5.0 | 2.0 |
| 16 | 3775 | 114.5 | 691 | 157 | .394 | 742 | 6.5 | 1.6 |
| 18 | 5475 | 129.5 | 781 | 228 | .386 | 1056 | 8.2 | 1.2 |
| 20 | 7600 | 145 | 875 | 317 | - | - | - | - |
| P.R.= 1.2 | | | | | | | | |
| 10 | 900 | 77.5 | 468 | 38 | >.420 | >192 | >72.7 | + |
| 12 | 1600 | 92.5 | 558 | 67 | .420 | 338 | 3.9 | 2.6 |
| 14 | 2550 | 107.5 | 649 | 106 | .406 | 516 | 5.1 | 4.1 |
| 16 | 3850 | 123 | 742 | 160 | .393 | 755 | 6.6 | 3.1 |
| 18 | 5575 | 139 | 839 | 232 | .384 | 1069 | 8.3 | 2.4 |
| 20 | 7725 | 155.5 | 938 | 322 | - | - | - | - |
| P.R.= 1.1 | | | | | | | | |
| 10 | 950 | 82.5 | 498 | 40 | >.420 | > 202 | > 2.8 | + |
| 12 | 1650 | 99.5 | 600 | 69 | >.423 | > 350 | > 4.1 | 7.9 |
| 14 | 2625 | 115.5 | 697 | 109 | .408 | 547 | 5.4 | 10.2 |
| 16 | 3950 | 131.5 | 793 | 165 | .393 | 778 | 6.8 | 6.2 |
| 18 | 5725 | 148.5 | 896 | 239 | .383 | 1098 | 8.5 | 4.9 |
| 20 | 7950 | 166.5 | 1004 | 331 | - | - | - | - |
| P.R.= 1.0 | | | | | | | | |
| 10 | 975 | 89.5 | 540 | 41 | >.420 | > 206 | > 2.9 | + |
| 12 | 1725 | 107 | 646 | 72 | >.420 | > 363 | > 4.2 | > 10.5 |
| 14 | 2725 | 124 | 748 | 114 | .409 | 560 | 5.6 | 14.3 |
| 16 | 4100 | 142 | 857 | 171 | .394 | 808 | 7.0 | 9.4 |
| 18 | 5925 | 160.5 | 968 | 247 | - | - | - | - |
| 20 | 8275 | 180.5 | 1089 | 345 | - | - | - | - |
| P.R.= 0.9 | | | | | | | | |
| 10 | 1050 | 98 | 591 | 44 | > .420 | > 221.8 | > 3.1 | + |
| 12 | 1825 | 117.5 | 709 | 76 | > .420 | > 384 | > 4.5 | > 18.4 |
| 14 | 2900 | 136 | 821 | 121 | .412 | 598.8 | > 6.0 | > 22 |
| 16 | 4450 | 155 | 935 | 185 | - | - | - | - |
| 18 | 6275 | 175 | - | - | - | - | - | - |
| 20 | - | - | - | - | - | - | - | - |
| P.R.= 0.8 | | | | | | | | |
| 10 | 1150 | 109 | 658 | 48 | > .420 | > 242 | > 3.4 | + |
| 12 | 2000 | 130 | 784 | 83 | > .420 | > 419 | > 4.9 | > 29 |
| 14 | 3225 | 152 | 917 | 134 | - | - | - | - |
| 16 | 4800 | 173 | 1044 | 200 | - | - | - | - |
| 18 | - | - | - | - | - | - | - | - |
| 20 | - | - | - | - | - | - | - | - |

Note: > indicates values which were approximated.

# APPENDIX C

## WHEC SINGLE PROPELLER OPERATION FUEL CONSUMPTION DATA

## FUEL CONSUMPTION DATA

Escher Wyss Propeller - Trail Shaft

| Knots | Pitch | Shaft Horsepower | Shaft RPM | Engine RPM | Bhp/cyl | BSFC (lb/Bhp-hr) | Fuel Consumption (lb/hr/eng) | Fuel Consumption (gal/mi/eng) | Δ % from Lowest Value (Volume Rate) |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 1.4 | 1160 | 81.5 | 492 | 96.7 | .405 | 470 | 6.6 | 3.1 |
| 12 | 1.4 | 2025 | 97.5 | 589 | 169 | .397 | 805 | 9.3 | 2.2 |
| 14 | 1.4 | 3225 | 113.5 | 685 | 269 | - | - | - | - |
| 16 | 1.4 | 4875 | 129.5 | 781 | 406 | - | - | - | - |
| 10 | 1.3 | 1140 | 86.5 | 522 | 95 | .405 | 462 | 6.4 | 0 |
| 12 | 1.3 | 2000 | 97.5 | 588 | 167 | .397 | 796 | 9.2 | 1.1 |
| 14 | 1.3 | 3200 | 113.5 | 685 | 267 | - | - | - | - |
| 16 | 1.3 | 4825 | 137.5 | 830 | 403 | - | - | - | - |
| 8 | 1.2 | 600 | 73.5 | 443 | 50 | ~.425 | ~ 255 | ~ 4.4 | ~ 2.3 |
| 10 | 1.2 | 1125 | 92 | 555 | 94 | .407 | 459 | 6.4 | 0 |
| 12 | 1.2 | 1990 | 110.5 | 667 | 166 | .394 | 785 | 9.1 | 0 |
| 14 | 1.2 | 3160 | 128 | 772 | 263 | - | - | - | - |
| 16 | 1.2 | 4800 | 147 | 887 | 400 | - | - | - | - |
| 8 | 1.1 | 590 | 78 | 471 | 49 | ~.430 | ~ 253 | ~ 4.4 | ~ 2.3 |
| 10 | 1.1 | 1125 | 97.5 | 588 | 94 | .408 | 460 | 6.4 | 0 |
| 12 | 1.1 | 2000 | 117.5 | 709 | 167 | .392 | 786 | 9.1 | 0 |
| 14 | 1.1 | 3160 | 136 | 821 | 263 | .383 | 1209 | 12.0 | 0 |
| 16 | 1.1 | 4775 | 156 | 941 | 398 | - | - | - | - |
| 8 | 1.0 | 575 | 73.5 | 443 | 48 | ~.432 | ~ 249 | ~ 4.3 | 0 |
| 10 | 1.0 | 1150 | 105 | 634 | 96 | .409 | 471 | 6.6 | 3.1 |
| 12 | 1.0 | 2025 | 125.5 | 757 | 169 | .392 | 795 | 9.2 | 1.1 |
| 14 | 1.0 | 3200 | 146.5 | 884 | 267 | .380 | 1218 | 12.1 | 0.1 |
| 16 | 1.0 | 4825 | 167.5 | 1011 | 669 | - | - | - | - |
| 8 | 0.9 | 590 | 91 | 550 | 49 | ~.438 | ~ 258 | ~ 4.5 | 4.7 |
| 10 | 0.9 | 1175 | 113.5 | 685 | 98 | .413 | 486 | 6.8 | 6.3 |
| 12 | 0.9 | 2075 | 136.5 | 824 | 173 | .393 | 816 | 9.5 | 8.2 |
| 14 | 0.9 | 3275 | 159 | 959 | 273 | - | - | - | - |
| 16 | 0.9 | 4950 | 181.5 | 1095 | 413 | - | - | - | - |
| 8 | 0.8 | 625 | 100 | 603 | 52 | ~.440 | ~ 275 | ~ 4.8 | 11.6 |
| 10 | 0.8 | 1225 | 126 | 760 | 102 | .417 | 510 | 7.11 | 10.9 |
| 12 | 0.8 | 2175 | 150.5 | 908 | 181 | - | - | - | - |
| 14 | 0.8 | 3425 | 175 | 1056 | 285 | - | - | - | - |

NOTE: ~ indicates that the BSFC value was extrapolated from the engine map.

## FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

**Propulsion Systems Inc. Propellers - Trail Shaft**

| Knots | Pitch | Shaft Horsepower | Shaft RPM | Engine RPM | Bhp/cyl | BSFC (lb/Bhp-hr) | Fuel Consumption (lb/hr/eng) | Fuel Consumption (gal/mi/eng) | Δ % from Lowest Value (Volume Rate) |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 1.4 | 1325 | 81.5 | 492 | 110 | .401 | 529 | 7.4 | 0 |
| 12 | 1.4 | 2325 | 97.5 | 588 | 194 | .400 | 931 | 10.8 | 4.9 |
| 14 | 1.4 | 3700 | 113.5 | 685 | 308 | - | - | - | - |
| 16 | 1.4 | 5600 | 129.5 | 781 | 467 | - | - | - | - |
| 10 | 1.3 | 1315 | 86.5 | 522 | 110 | .400 | 528 | 7.4 | 0 |
| 12 | 1.3 | 2300 | 113.5 | 685 | 192 | .395 | 910 | 10.6 | 2.9 |
| 14 | 1.3 | 3650 | 120 | 724 | 304 | - | - | - | - |
| 16 | 1.3 | 5525 | 138 | 833 | 460 | - | - | - | - |
| 8 | 1.2 | 650 | 73 | 440 | 51 | ~.425 | ~ 260 | ~ 4.5 | 0 |
| 10 | 1.2 | 1315 | 92 | 555 | 110 | .400 | 528 | 7.4 | 0 |
| 12 | 1.2 | 2275 | 110 | 664 | 190 | .394 | 898 | 10.4 | 1.0 |
| 14 | 1.2 | 3625 | 128.5 | 775 | 302 | - | - | - | - |
| 16 | 1.2 | 5500 | 147 | 887 | 458 | - | - | - | - |
| 8 | 1.1 | 650 | 78 | 471 | 54 | ~.425 | ~ 275 | ~ 4.8 | 6.7 |
| 10 | 1.1 | 1325 | 98 | 591 | 110 | .401 | 529 | 7.4 | 0 |
| 12 | 1.1 | 2275 | 117.5 | 709 | 190 | .390 | 889 | 10.3 | 0 |
| 14 | 1.1 | 3625 | 136.5 | 824 | 302 | - | - | - | - |
| 16 | 1.1 | 5475 | 156 | 941 | 456 | - | - | - | - |
| 8 | 1.0 | 660 | 83.5 | 504 | 55 | ~.427 | ~ 282 | ~ 4.9 | 8.9 |
| 10 | 1.0 | 1325 | 115 | 694 | 110 | .408 | 539 | 7.5 | 1.4 |
| 12 | 1.0 | 2300 | 125.5 | 757 | 192 | .388 | 894 | 10.4 | 1.0 |
| 14 | 1.0 | 3675 | 146 | 881 | 306 | - | - | - | - |
| 16 | 1.0 | 5575 | 167.5 | 1011 | 465 | - | - | - | - |
| 8 | 0.9 | 675 | 91 | 549 | 50 | ~.430 | ~ 289 | ~ 5.0 | 11.1 |
| 10 | 0.9 | 1350 | 114 | 688 | 113 | .405 | 549 | 7.7 | 2.7 |
| 12 | 0.9 | 2375 | 136.5 | 824 | 198 | .388 | 922 | 10.7 | 3.9 |
| 14 | 0.9 | 3775 | 159 | 959 | 315 | - | - | - | - |
| 16 | 0.9 | 5675 | 181.5 | 1095 | 473 | - | - | - | - |
| 8 | 0.8 | 725 | 100.5 | 606 | 60 | ~.432 | ~ 311 | ~ 5.4 | 20 |
| 10 | 0.8 | 1425 | 126 | 760 | 119 | .408 | 583 | 8.1 | 9.5 |
| 12 | 0.8 | 2500 | 150.5 | 908 | 208 | - | - | - | - |
| 14 | 0.8 | 3950 | 175.5 | 1059 | 329 | - | - | - | - |

NOTE: ~ indicates that the BSFC value was extrapolated from the engine map

FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

Escher Wyss Propeller - Locked Shaft

| Knots | Pitch | Shaft Horsepower | Shaft RPM | Engine RPM | Bhp/cyl | BSFC (lb/Bhp-hr) | Fuel Consumption (lb/hr/eng) | Fuel Consumption (gal/mi/eng) | Δ % from Lowest Value (Volume Rate) |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 1.4 | 1125 | 75.5 | 456 | 94 | .406 | 458 | 8.0 | 3.9 |
| 10 | 1.4 | 2225 | 94.5 | 570 | 185 | .400 | 888 | 12.4 | 5.2 |
| 12 | 1.4 | 3900 | 113.5 | 685 | 325 | - | - | - | - |
| 14 | 1.4 | 6150 | 131.5 | 793 | 513 | - | - | - | - |
| 8 | 1.3 | 1100 | 79.5 | 480 | 92 | .406 | 448 | 7.8 | 2.6 |
| 10 | 1.3 | 2200 | 100 | 603 | 183 | .397 | 872 | 12.1 | 4.3 |
| 12 | 1.3 | 3825 | 120 | 724 | 319 | - | - | - | - |
| 14 | 1.3 | 6025 | 139.5 | 842 | 502 | - | - | - | - |
| 8 | 1.2 | 1090 | 85 | 513 | 91 | .406 | 443 | 7.7 | 0 |
| 10 | 1.2 | 2175 | 106.5 | 643 | 181 | .395 | 858 | 12.0 | 3.4 |
| 12 | 1.2 | 3750 | 127 | 766 | 313 | - | - | - | - |
| 14 | 1.2 | 5925 | 148 | 893 | 494 | - | - | - | - |
| 8 | 1.1 | 1075 | 89.5 | 540 | 90 | .407 | 440 | 7.7 | 0 |
| 10 | 1.1 | 2150 | 113 | 682 | 179 | .393 | 844 | 11.8 | 1.7 |
| 12 | 1.1 | 3725 | 135 | 815 | 310 | - | - | - | - |
| 14 | 1.1 | 5875 | 156.5 | 944 | 490 | - | - | - | - |
| 8 | 1.0 | 1075 | [illegible] | 576 | 90 | .409 | 442 | 7.7 | 0 |
| 10 | 1.0 | 2125 | [illegible] | 724 | 177 | .391 | 830 | 11.6 | 0 |
| 12 | 1.0 | 3725 | 144 | 869 | 310 | - | - | - | - |
| 14 | 1.0 | 5875 | 167.5 | 1011 | 490 | - | - | - | - |
| 8 | 0.9 | 1075 | 103.5 | 525 | 90 | .412 | 445 | 7.7 | 0 |
| 10 | 0.9 | 2150 | 129.5 | 781 | 179 | .390 | 838 | 11.7 | 0.8 |
| 12 | 0.9 | 3750 | 155 | 935 | 313 | - | - | - | - |
| 14 | 0.9 | 5925 | 180 | 1086 | 494 | - | - | - | - |
| 8 | 0.8 | 1100 | 113 | 682 | 92 | .415 | 458 | 8.0 | 3.9 |
| 10 | 0.8 | 2225 | 142.5 | 860 | 185 | .392 | 870 | 12.1 | 4.3 |
| 12 | 0.8 | 3825 | 170.5 | 1029 | 319 | - | - | - | - |

FUEL CONSUMPTION DATA

USCG 378-Foot WHEC Single Propeller Operation

| Knots | Pitch | Shaft Horsepower | Propulsion Systems Inc. Propellers - Locked Shaft: Shaft RPM | Engine RPM | Bhp/cyl | BSFC (lb/Bhp-hr) | Fuel Consumption (lb/hr/eng) | Fuel Consumption (gal/mi/eng) | Δ % from Lowest Value (Volume Rate) |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 1.4 | 1275 | 75.5 | 456 | 106 | .405 | 515 | 9.0 | 4.7 |
| 10 | 1.4 | 2575 | 94.5 | 570 | 215 | - | - | - | - |
| 12 | 1.4 | 4475 | 113.5 | 685 | 373 | - | - | - | - |
| 14 | 1.4 | 7025 | 131.5 | 793 | 585 | - | - | - | - |
| 8 | 1.3 | 1250 | 79.5 | 480 | 104 | .403 | 503 | 8.8 | 2.3 |
| 10 | 1.3 | 2500 | 100.5 | 606 | 208 | - | - | - | - |
| 12 | 1.3 | 4375 | 120.0 | 724 | 365 | - | - | - | - |
| 14 | 1.3 | 6875 | 139 | 639 | 573 | - | - | - | - |
| 8 | 1.2 | 1250 | 84.5 | 510 | 104 | .402 | 502 | 8.7 | 1.2 |
| 10 | 1.2 | 2475 | 106.5 | 643 | 206 | .396 | 979 | 13.6 | 3.8 |
| 12 | 1.2 | 4275 | 127.5 | 769 | 356 | - | - | - | - |
| 14 | 1.2 | 6775 | 148 | 893 | 565 | - | - | - | - |
| 8 | 1.1 | 1225 | 89.5 | 540 | 102 | .403 | 493 | 8.6 | 0 |
| 10 | 1.1 | 2400 | 112.5 | 679 | 200 | .393 | 943 | 13.1 | 0 |
| 12 | 1.1 | 4225 | 135 | 815 | 352 | - | - | - | - |
| 14 | 1.1 | 6700 | 157 | 947 | 558 | - | - | - | - |
| 8 | 1.0 | 1225 | 95.5 | 576 | 102 | .404 | 494 | 8.6 | 0 |
| 10 | 1.0 | 2450 | 120 | 724 | 204 | .389 | 953 | 13.2 | 1.5 |
| 12 | 1.0 | 4225 | 144 | 869 | 352 | - | - | - | - |
| 14 | 1.0 | 6700 | 167 | 1008 | 558 | - | - | - | - |
| 8 | 0.9 | [illegible] | 103.5 | 624 | 102 | .407 | 498 | 8.7 | 1.2 |
| 10 | 0.9 | [illegible] | 129 | 778 | 204 | .387 | 947 | 13.2 | 0.8 |
| 12 | 0.9 | [illegible] | 155 | 935 | 358 | - | - | - | - |
| 14 | 0.9 | 6750 | 180.5 | 1089 | 563 | - | - | - | - |
| 8 | 0.8 | 1275 | 113.5 | 684 | 106 | .408 | 519 | 9.0 | 4.7 |
| 10 | 0.8 | 2525 | 142 | 857 | 210 | .386 | 973 | 13.6 | 3.8 |
| 12 | 0.8 | 4375 | 170.5 | 1029 | 365 | - | - | - | - |

# APPENDIX D

# REPORT OF NEW TECHNOLOGY

New operational techniques for improving the fuel consumption of the Coast Guard large cutters consisting of reprogramming pitch schedules to optimize fuel-consumption characteristics are discussed, and illustrated, on pages 6-16 to 6-35/6-36. These techniques offer fuel-economy improvements from 3 to 5 percent.

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